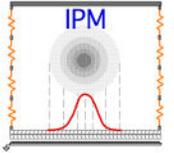


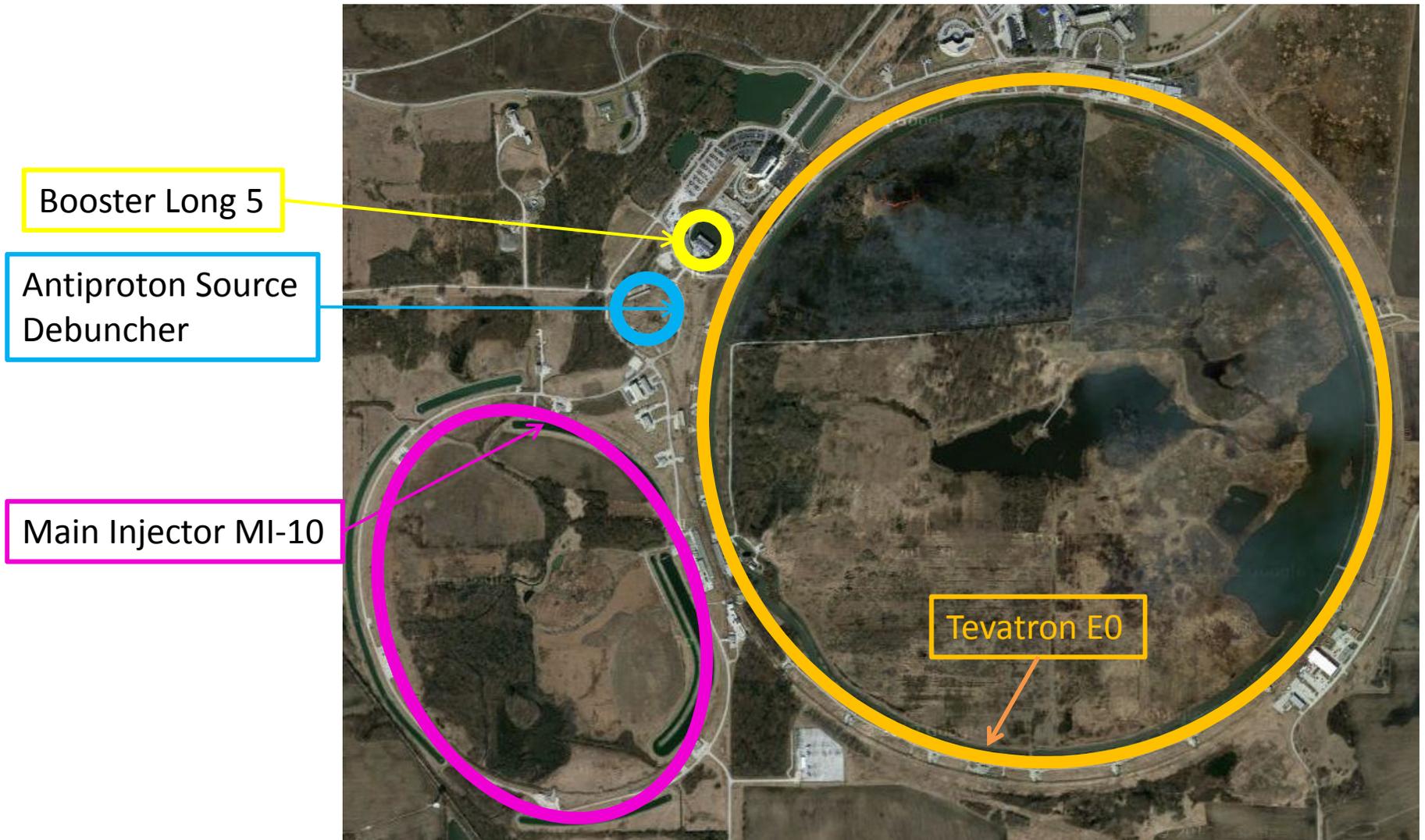
# Status of Profile Monitors @ Fermilab

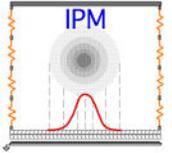
11 June 2013

Jim Zagel & Randy Thurman-Keup



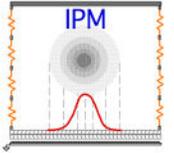
# IPM's in the Tev ERA



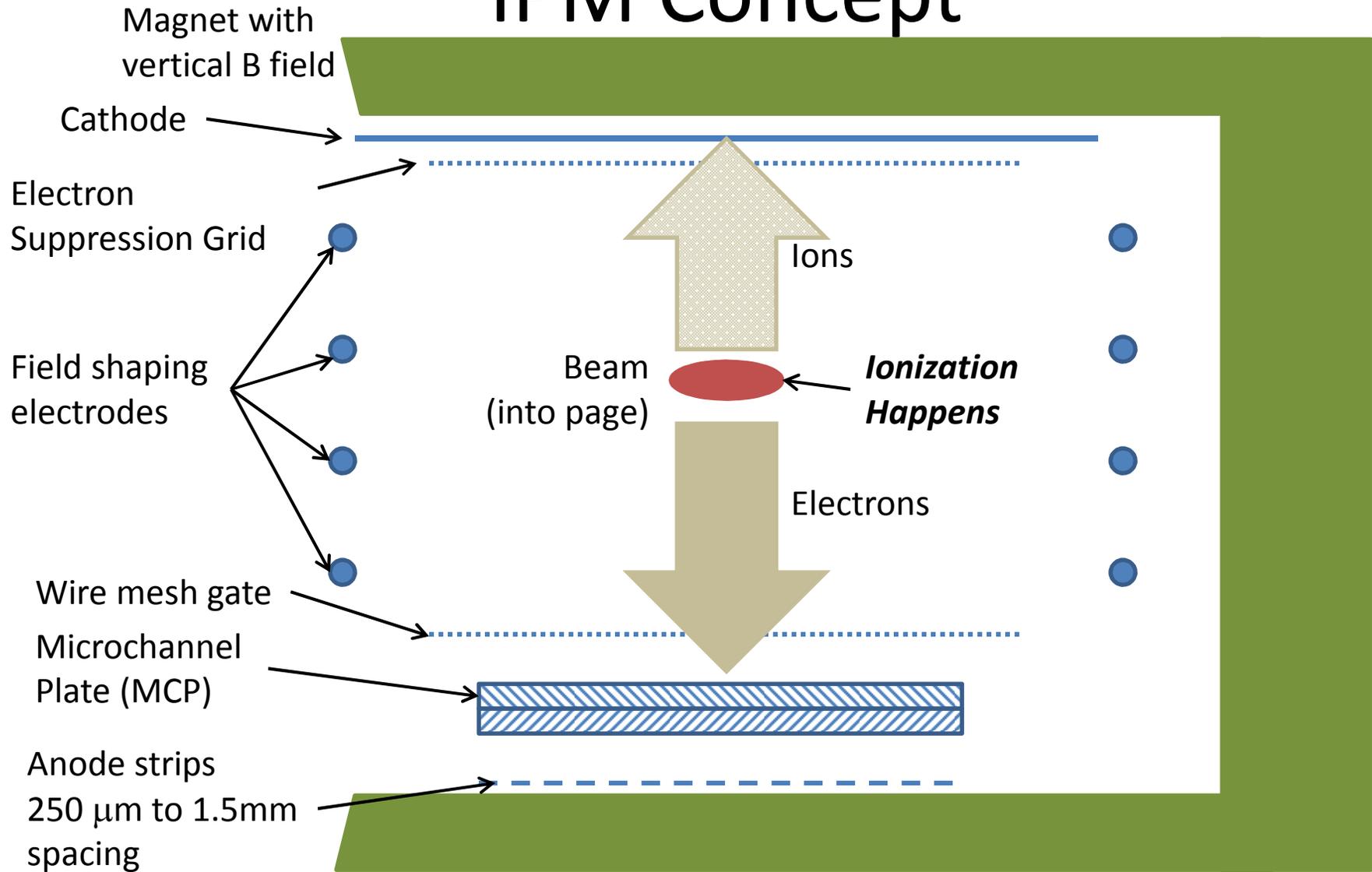


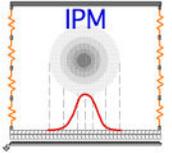
# IPM Basic Types

- Booster (400MeV – 8 GeV)
  - Electrostatic 10KV Clearing Field (Good at injection.)
- Main Ring Original (8 GeV -150GeV)
  - Electrostatic 30KV Clearing Field (Good at injection.)
- Recycler Ultra High Vacuum (8 GeV)
  - Electrostatic 30KV Clearing Field, e-11 Torr vacuum.
- Main Injector Mark-II (8 GeV -150GeV)
  - Permanent Magnetic Field 1KG and 10KV Clearing Field.
- Tevatron (150 GeV – 1 TeV)
  - Electro Magnet 1 KG and 10KV Clearing Field.

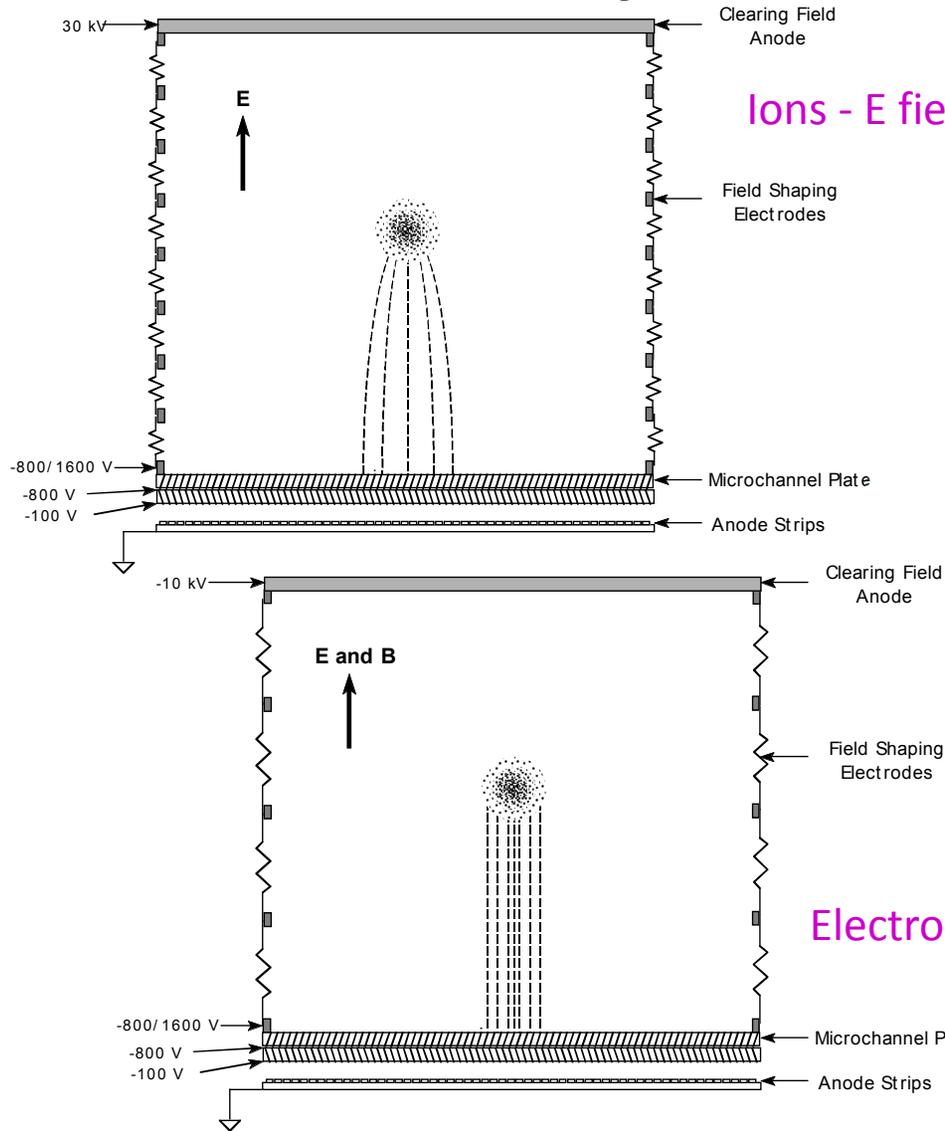


# IPM Concept



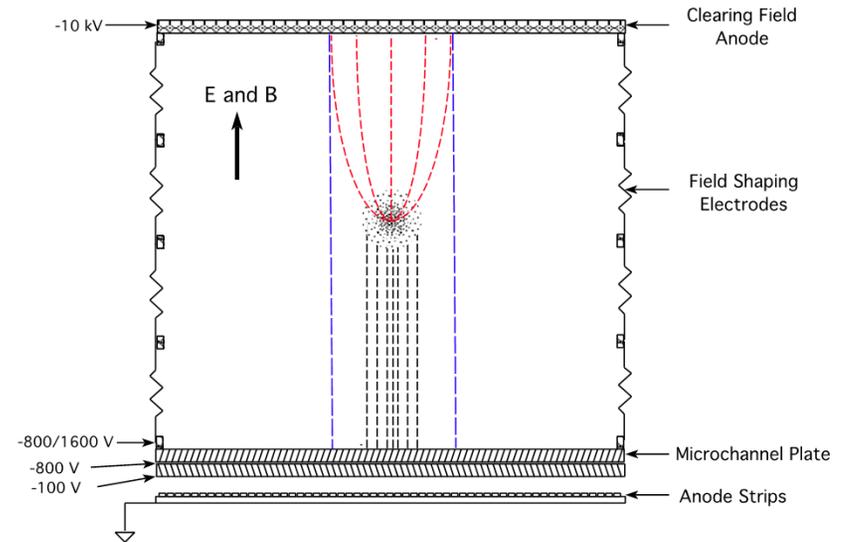


# Why the Magnetic Field



Ions - E field only

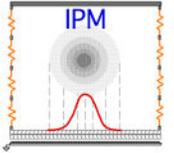
Ion / electron paths with E and B field



Mark II Ion Profile Monitor  
With Secondary Electrons

10/11/2010 jrjz

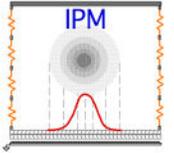
Electrons - E and B field



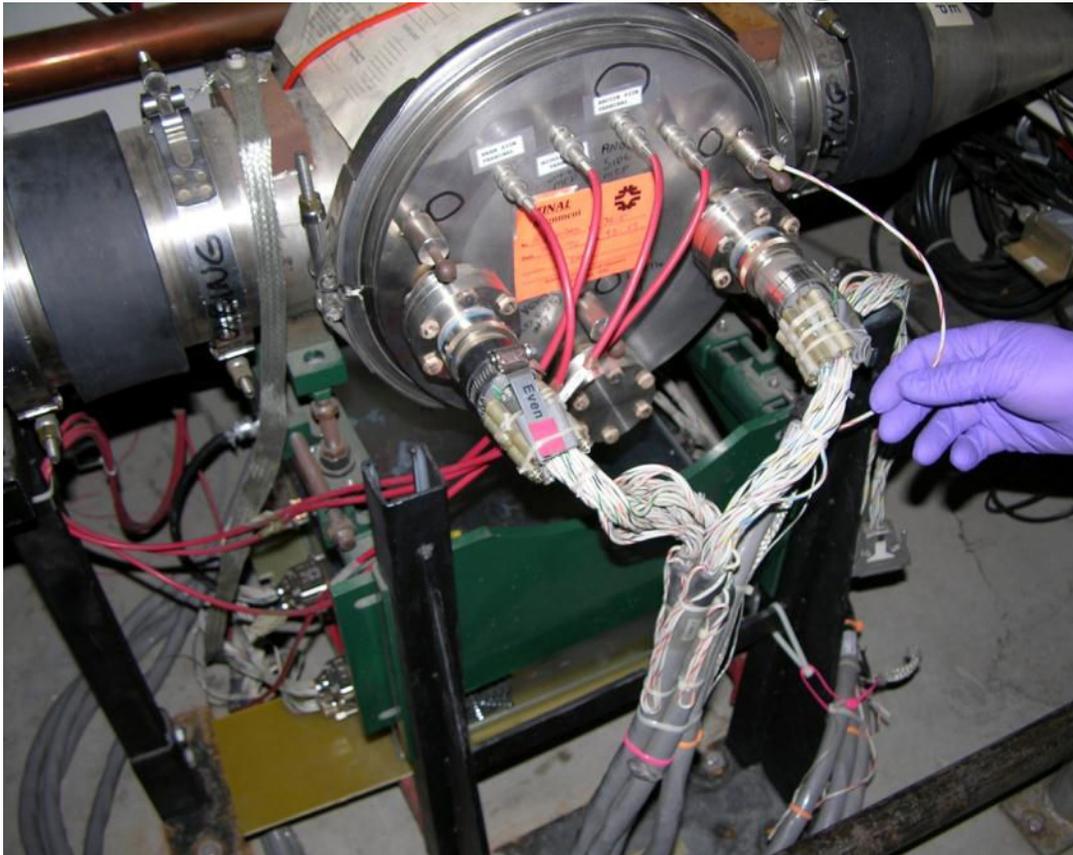
# Booster

Horizontal and Vertical co-located in Long 5

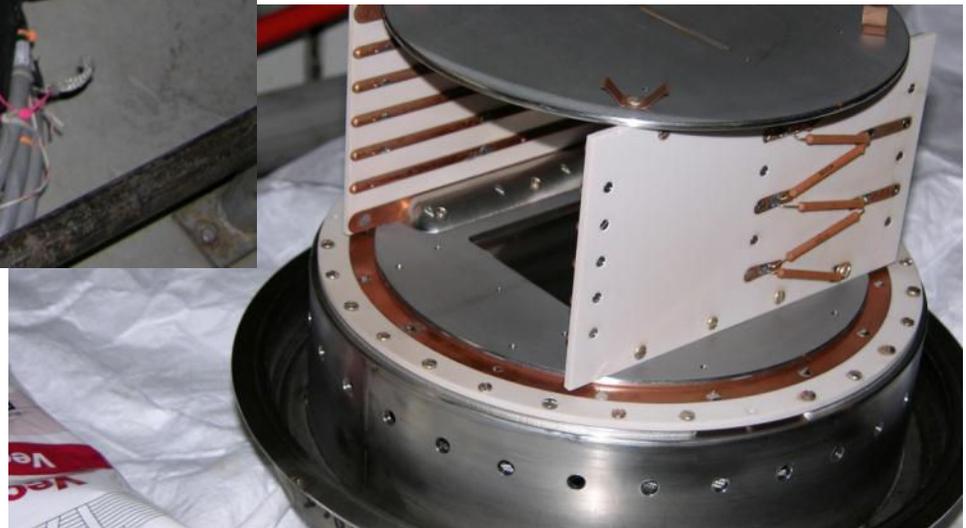


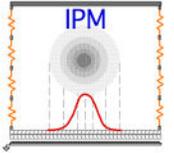


# Main Ring/MI Original



Vertical at Q103  
Also a Horizontal at Q102

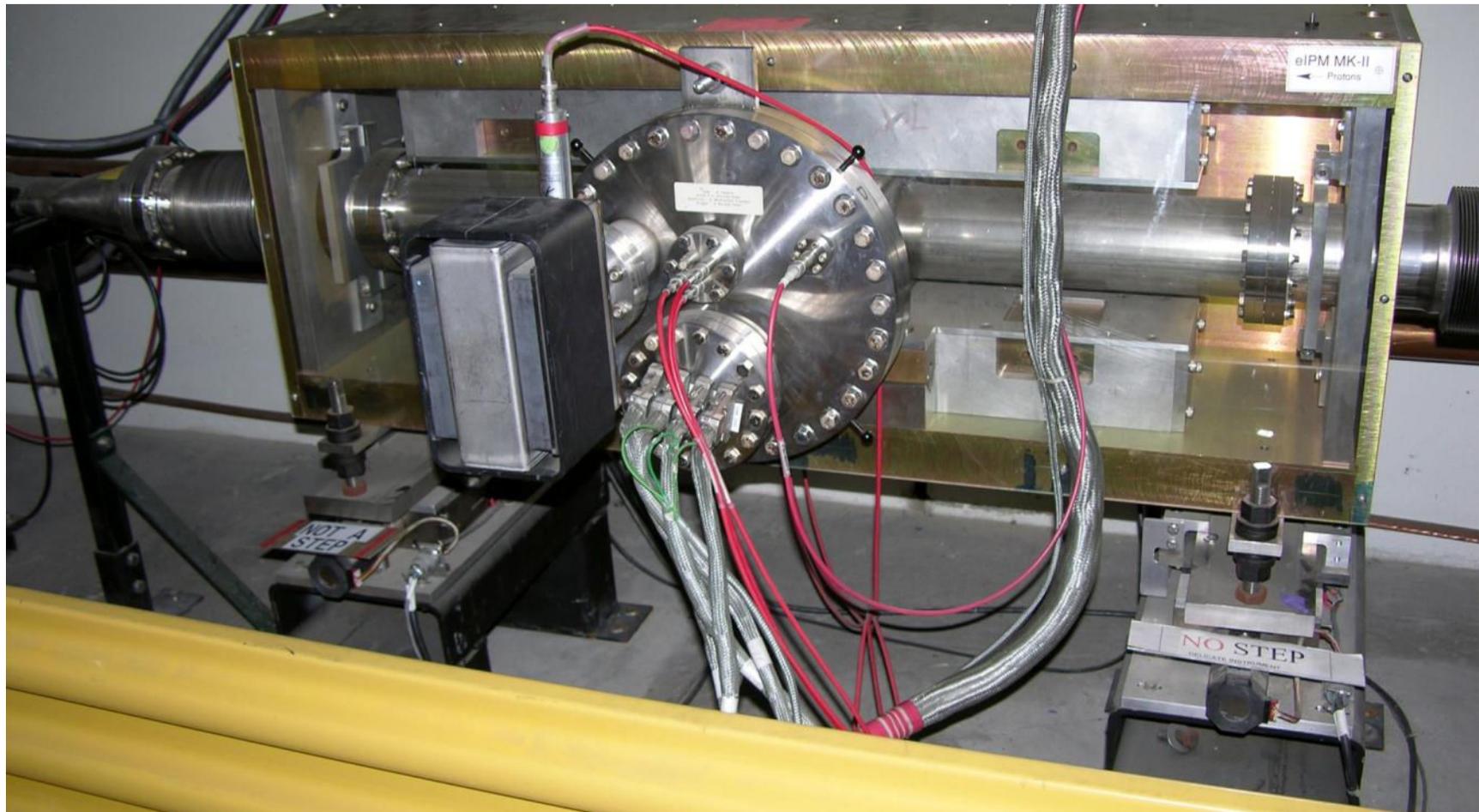


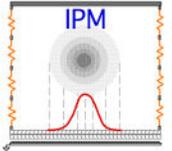


# Main Injector Mark-II

Horizontal Measurement Permanent Magnet at Q104

Independent up and downstream +/- 25mm in horizontal plane for alignment and MCP Exposure

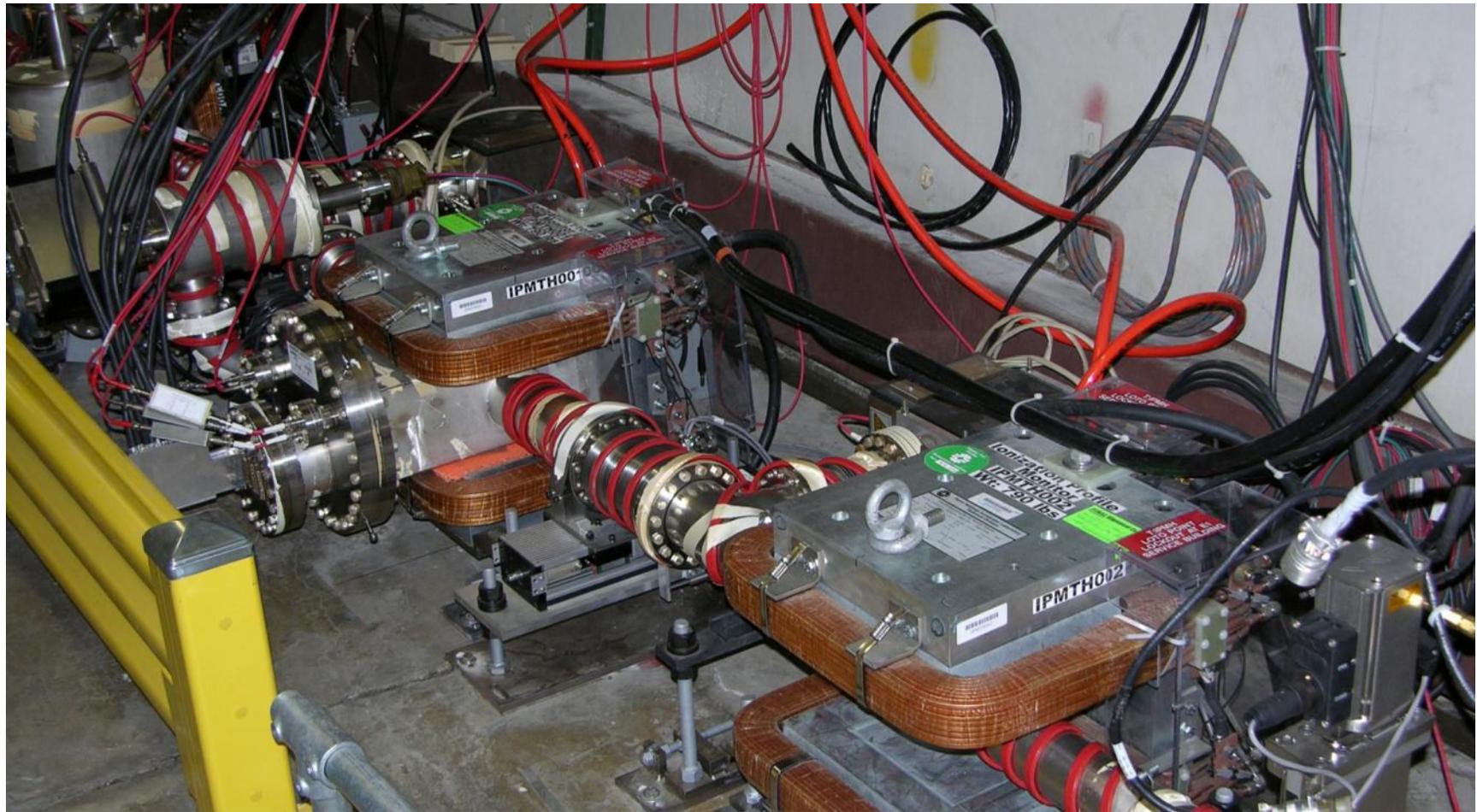




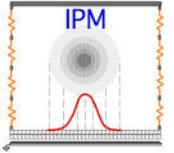
# Tevatron

Measured 36 Proton and 36 Anti-Proton bunches per turn using QIE Chips in tunnel.

Horizontal Detector

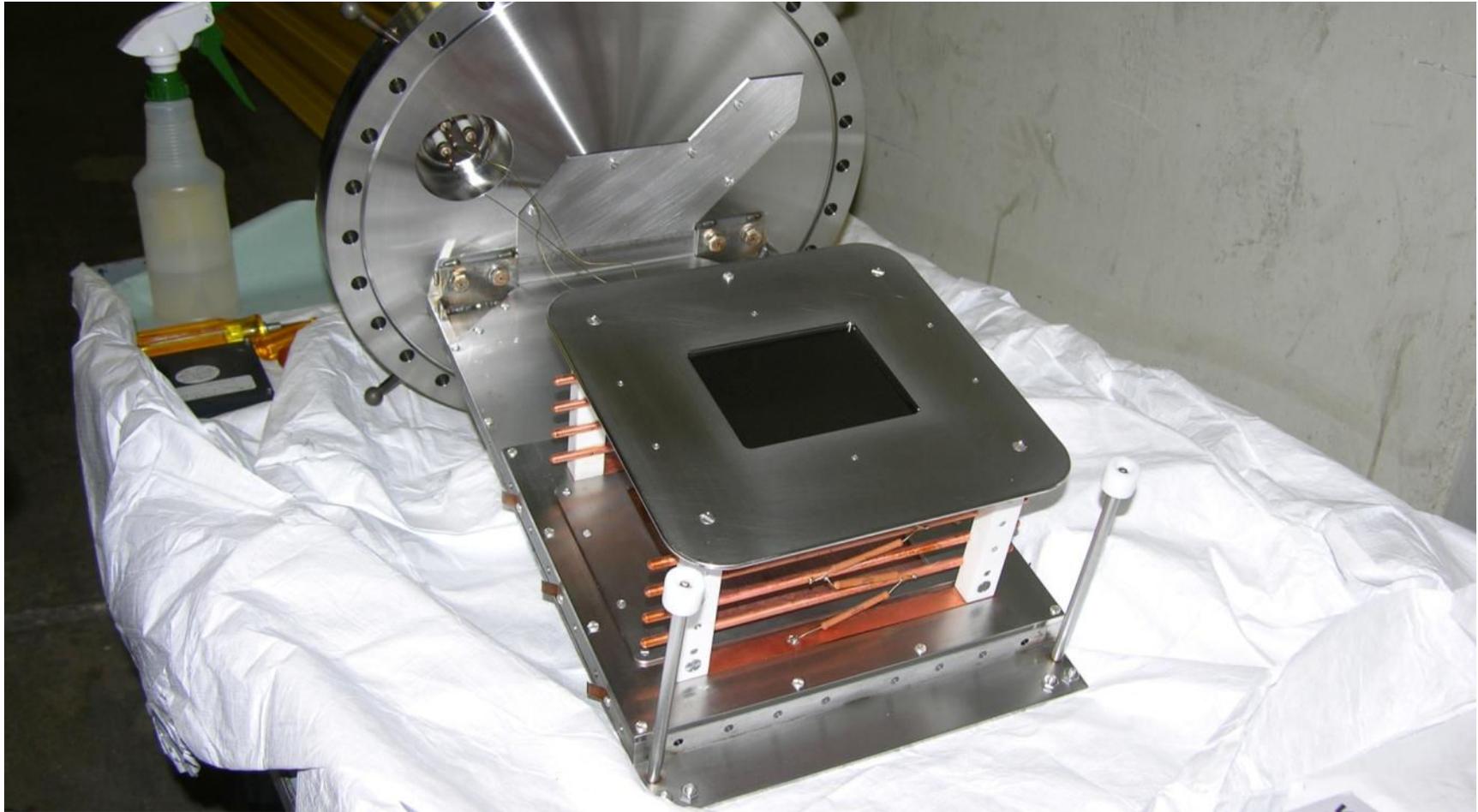


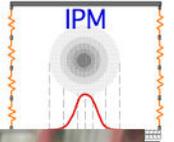
Horizontal Correction Magnet



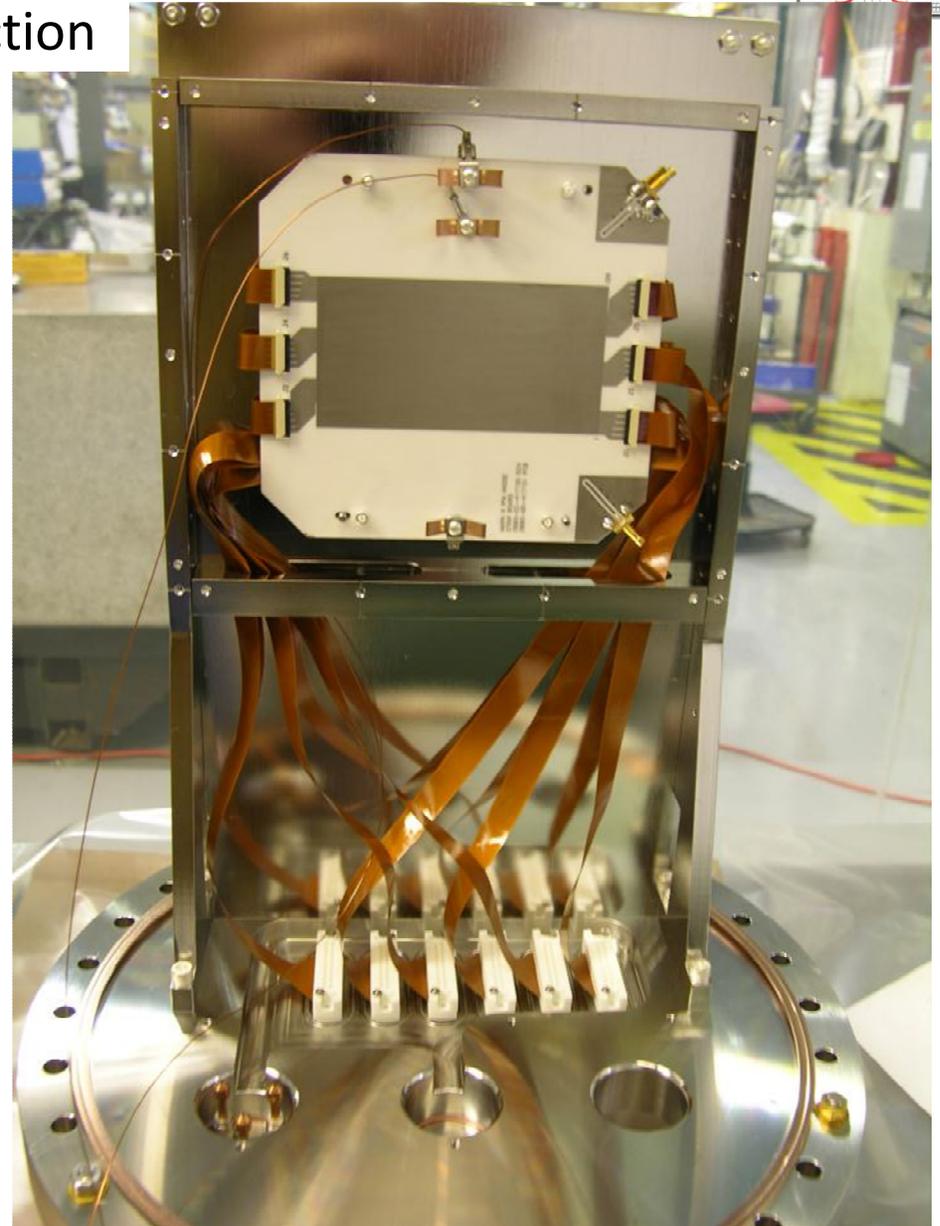
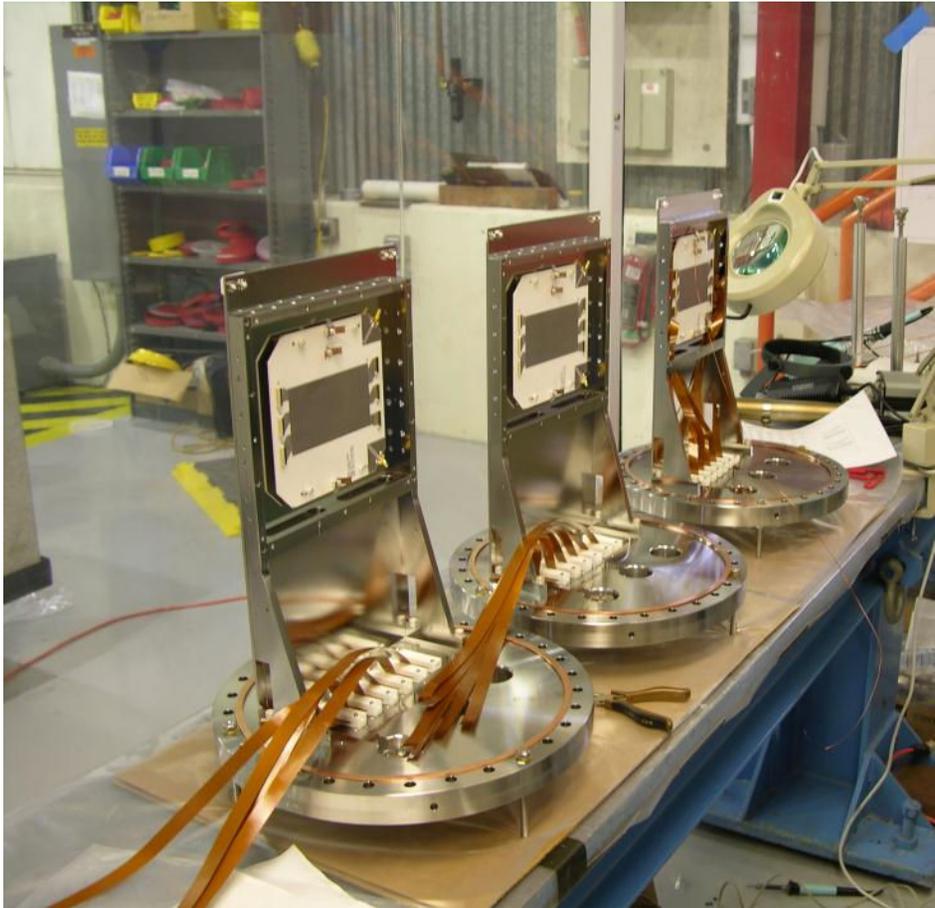
# Mark-II, and Tevatron Internals

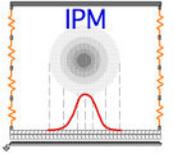
Tray design for quick extraction for MCP replacement, assures accurate realignment.



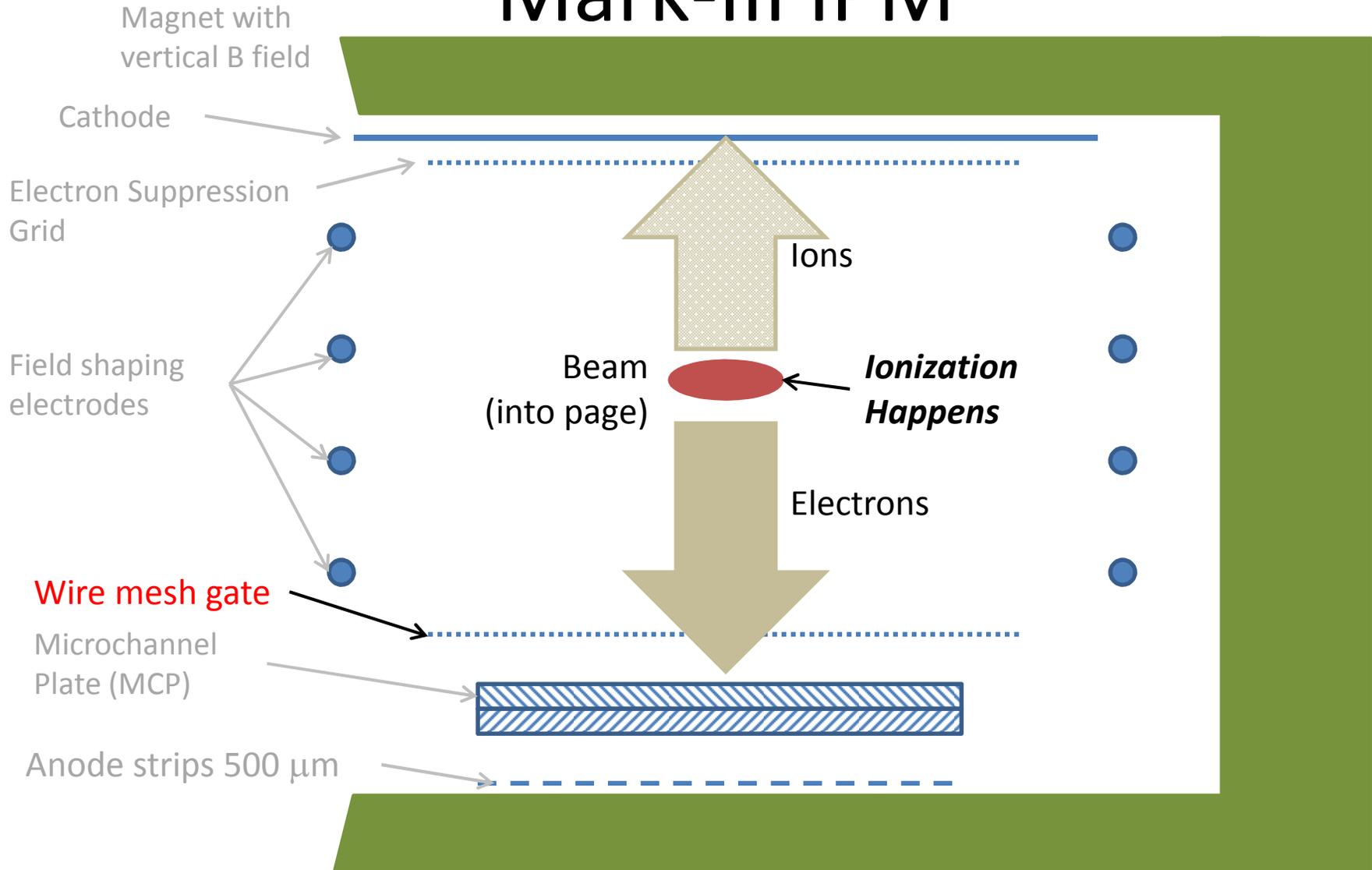


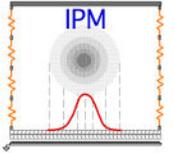
# Mark-III Internals Under Construction



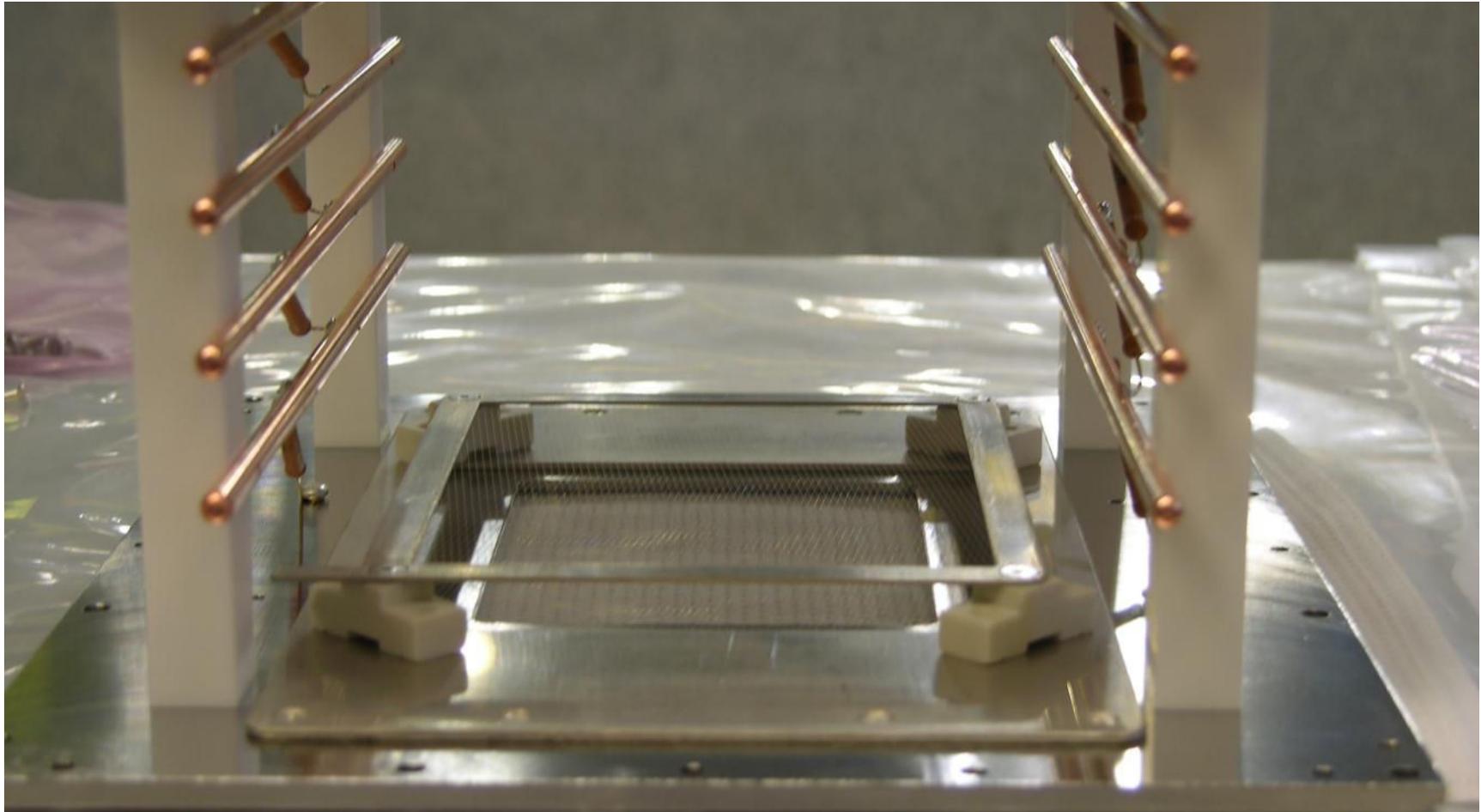


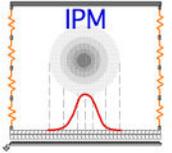
# Mark-III IPM





# Mark-III Control Grid

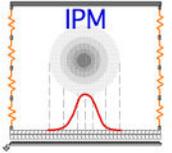




# Anode Strip Board

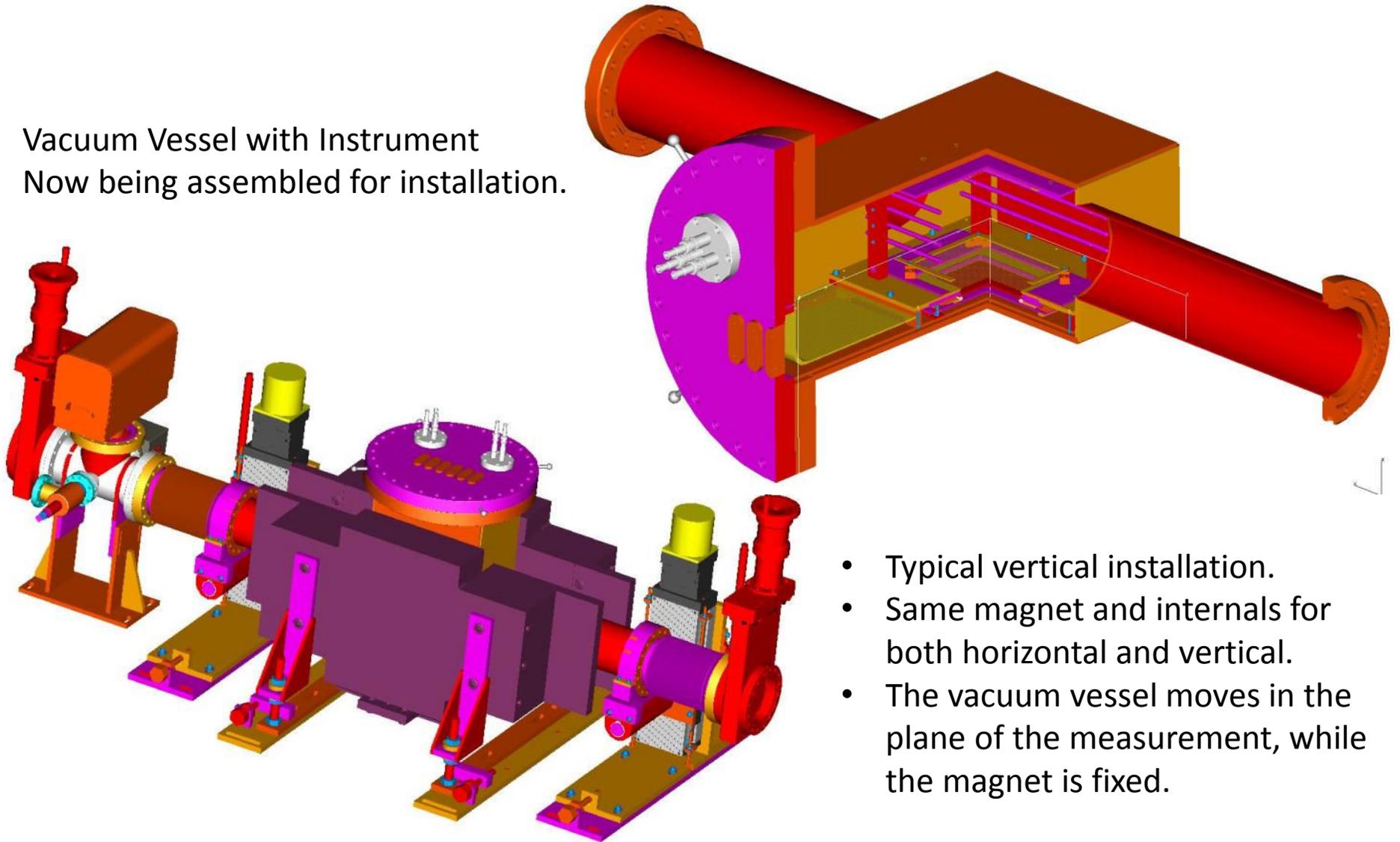
- Ceramic with mass terminated connectors.
  - 80% copper, 20% space.
- Booster
  - Beam sigma 4.5 mm
  - 60 Strips at 1.5 mm
  - $1.2E12$  to  $4.5E12$  protons
- Main Injector/Recycler
  - Beam sigma 4.5 - 1.5 mm
  - 120 Strips, pitch 0.5 mm
  - MI up to 6 booster batches
  - RR slip stack up to 12 batches
  - RR max intensity  $5E13$
- Tevatron
  - Beam sigma 1.5 mm
  - 128 strips, pitch 0.25 mm



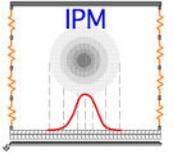


# Mark-III Model

Vacuum Vessel with Instrument  
Now being assembled for installation.



- Typical vertical installation.
- Same magnet and internals for both horizontal and vertical.
- The vacuum vessel moves in the plane of the measurement, while the magnet is fixed.



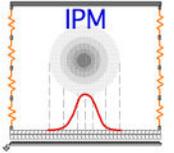
# Main Injector Mark-III Magnet

Magnet MIIPM001 on measurement stand for integral field map.

Similar to Mark-II but smaller.

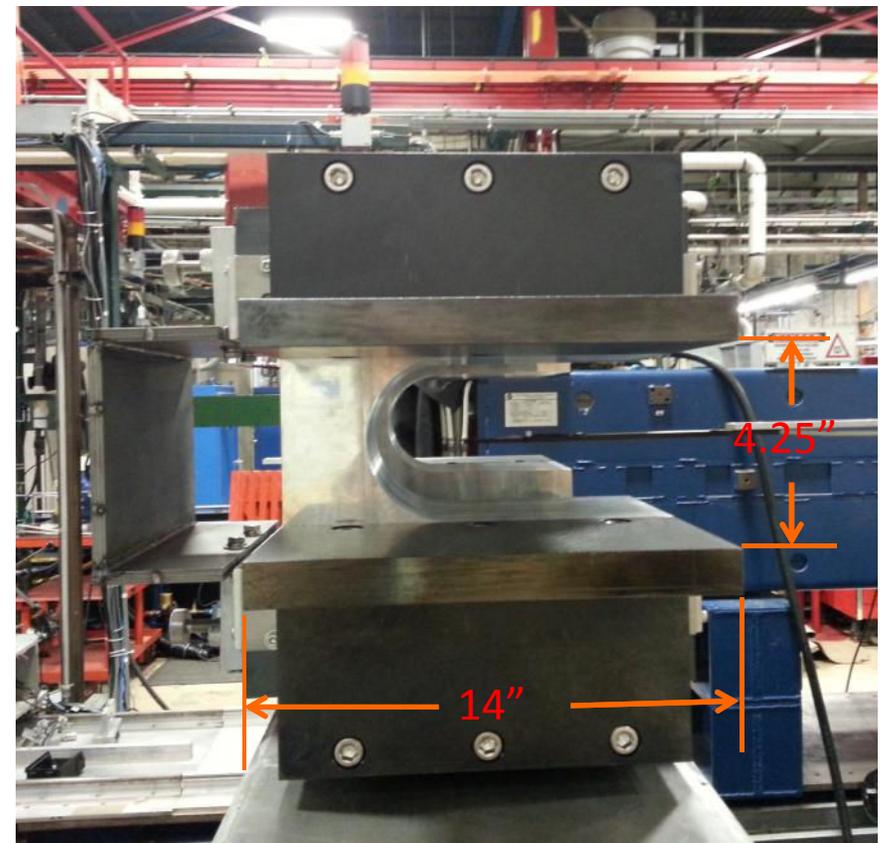
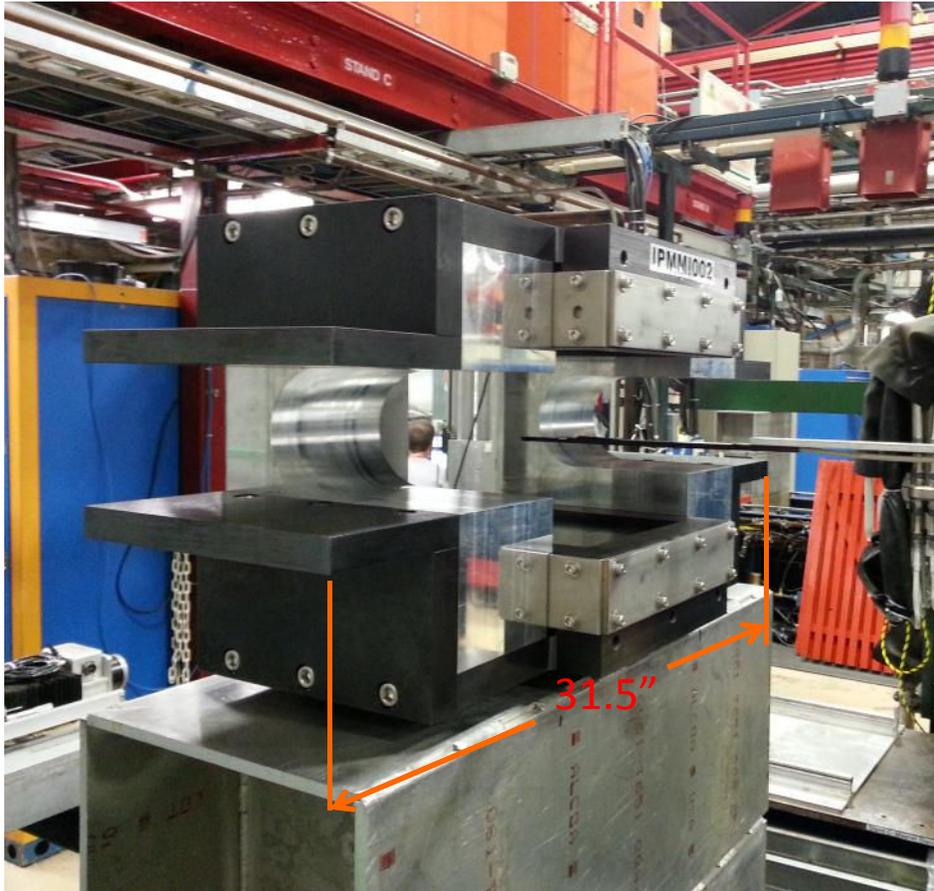
1KG center field and half correction up and downstream,  
Local 3 bump shunted, so beam sees close to zero integrated field.

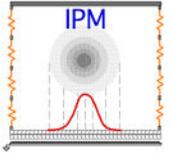




# MARK-III Magnet

Mounted on measurement stand  
for field quality map.  
Hall Probe shown.



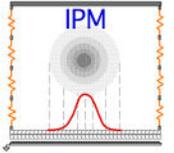


# MI Orbit Perturbation

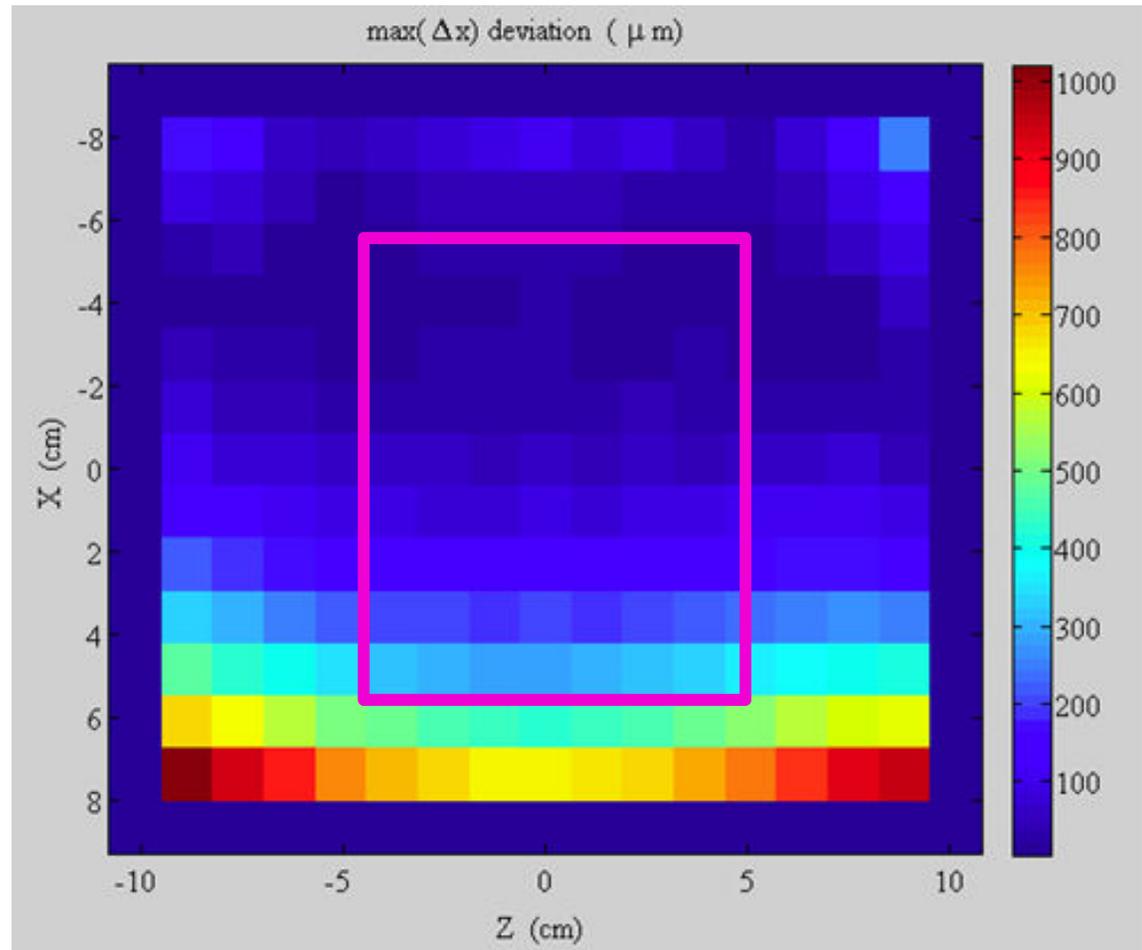
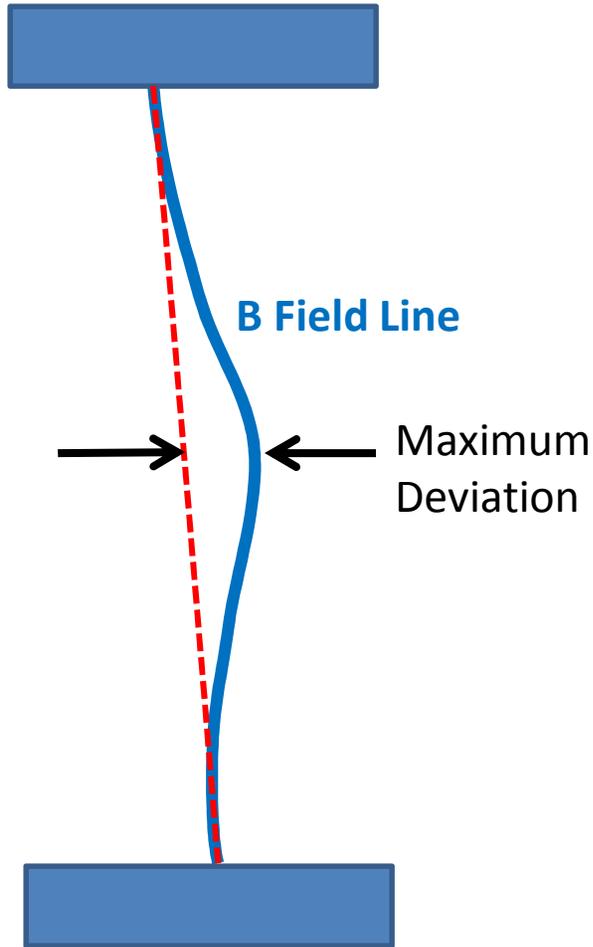
- Measured magnet integrated field is -0.001T-m
- Maximum displacement around the ring for the measured field integral is

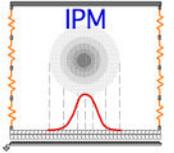
$$D = \frac{\int B_y dl}{\rho_m} \frac{\beta}{2 \sin \pi \nu}$$

For the Main Injector  $\rho_m \approx 27$  T-m  
and the maximum  $\beta$  is 50, Tune,  $\nu$  is 0.43,  
 $D \approx 0.001$  m



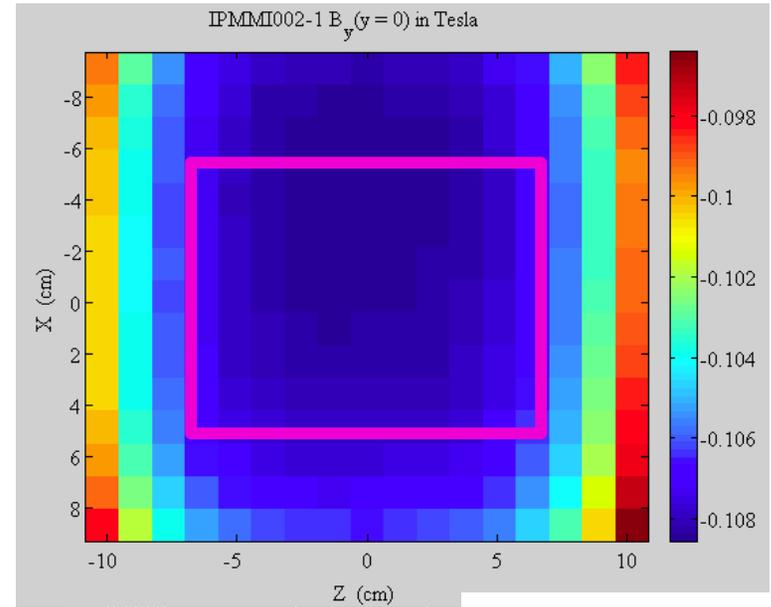
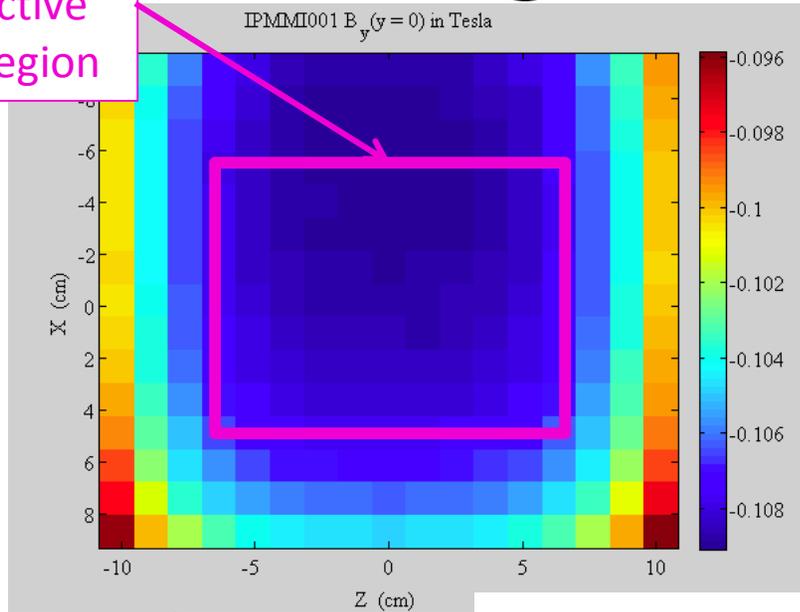
# Magnet Measurements



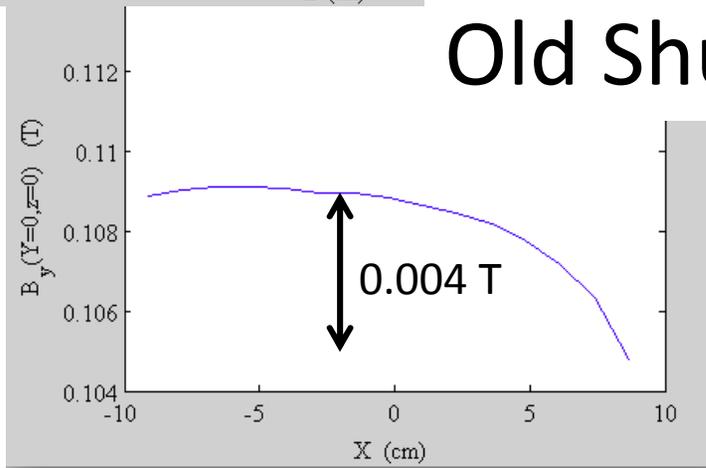


# Magnet Measurements

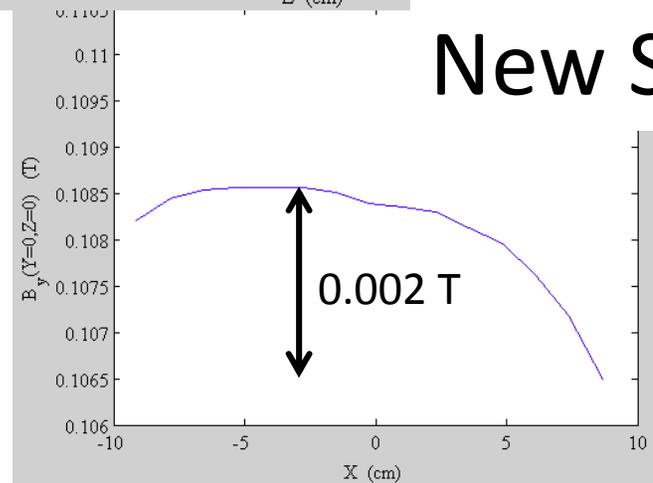
IPM  
Active  
Region

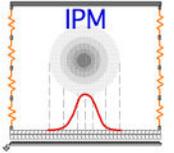


## Old Shunt

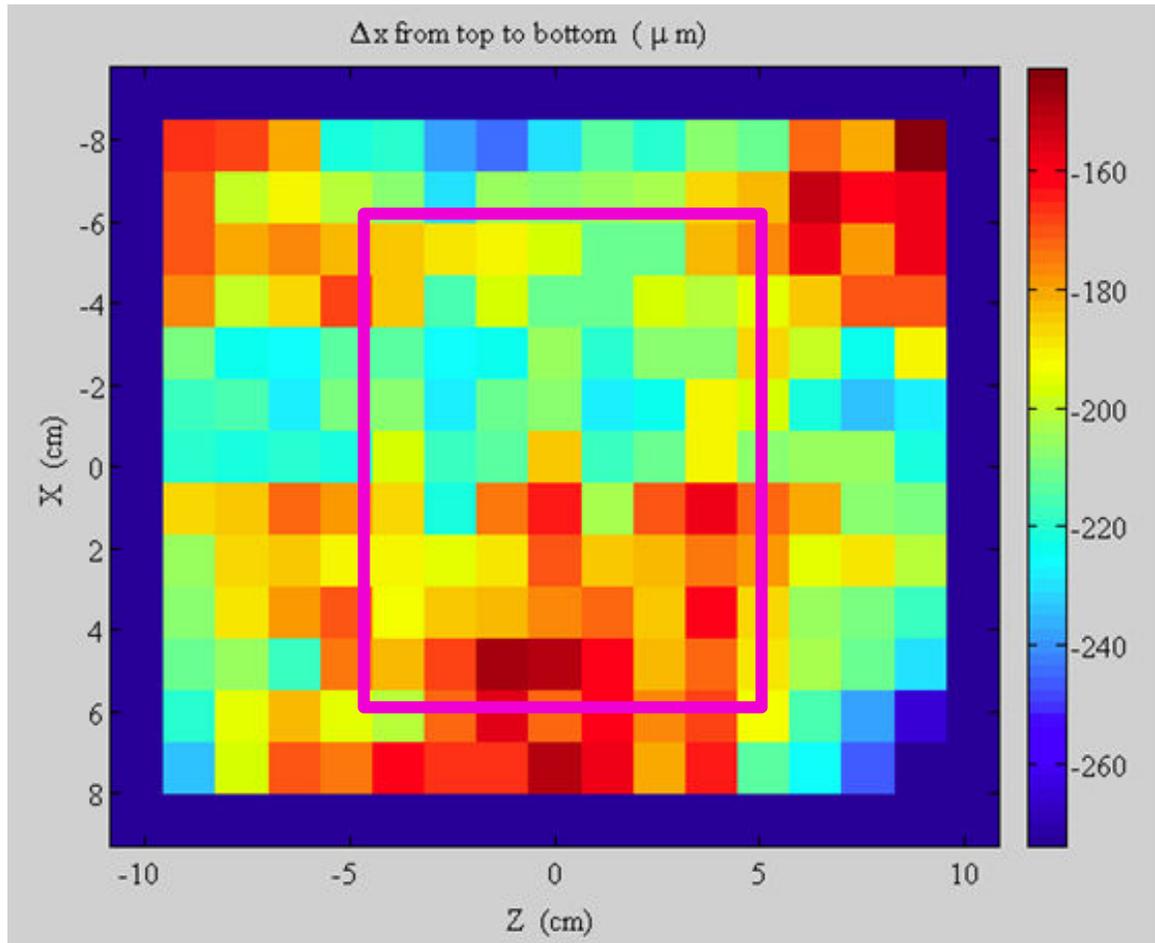
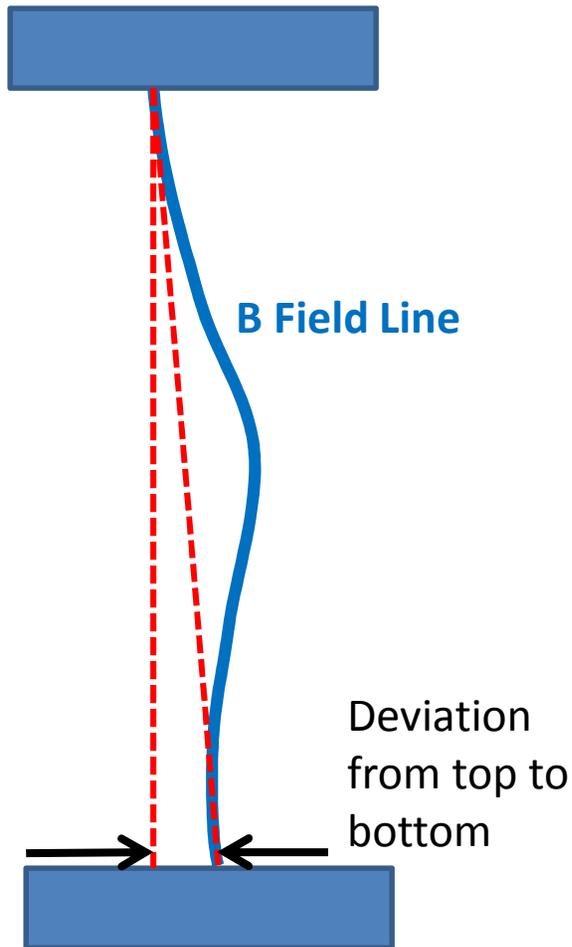


## New Shunt

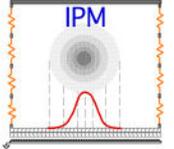




# Magnet Measurements

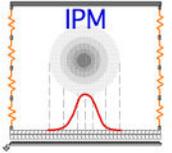


Average value of  $200\ \mu\text{m}$  could be hall probe rotation; corresponds to  $\sim 0.1$  degrees



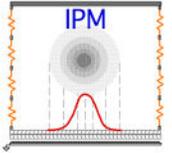
# Mark-III Vacuum Vessel





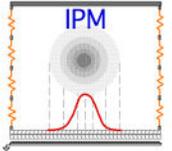
# IPM New Installation's

- New Main Injector
  - Magnetic Mark-III vertical at Q103
  - Mark-II internal parts will eventually be retrofitted.
- New Recycler Magnetic Mark-III
  - Horizontal at Q104
  - Vertical at Q103
- Booster
  - Will have 2 – 30KV Electrostatic cans available



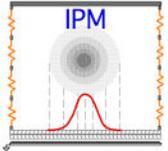
# IPM Measurement Capability

- All Systems
  - Turn by turn measurements.
    - Turns could be averaged for any accuracy desired.
  - Used for injection tuning/matching.
    - Routinely used for first 500 turns to see injection oscillations.
    - Sigma measurements anywhere in the cycle.
  - Collected 65K samples @ 1 per revolution
    - Booster 19900 turns for a full cycle.



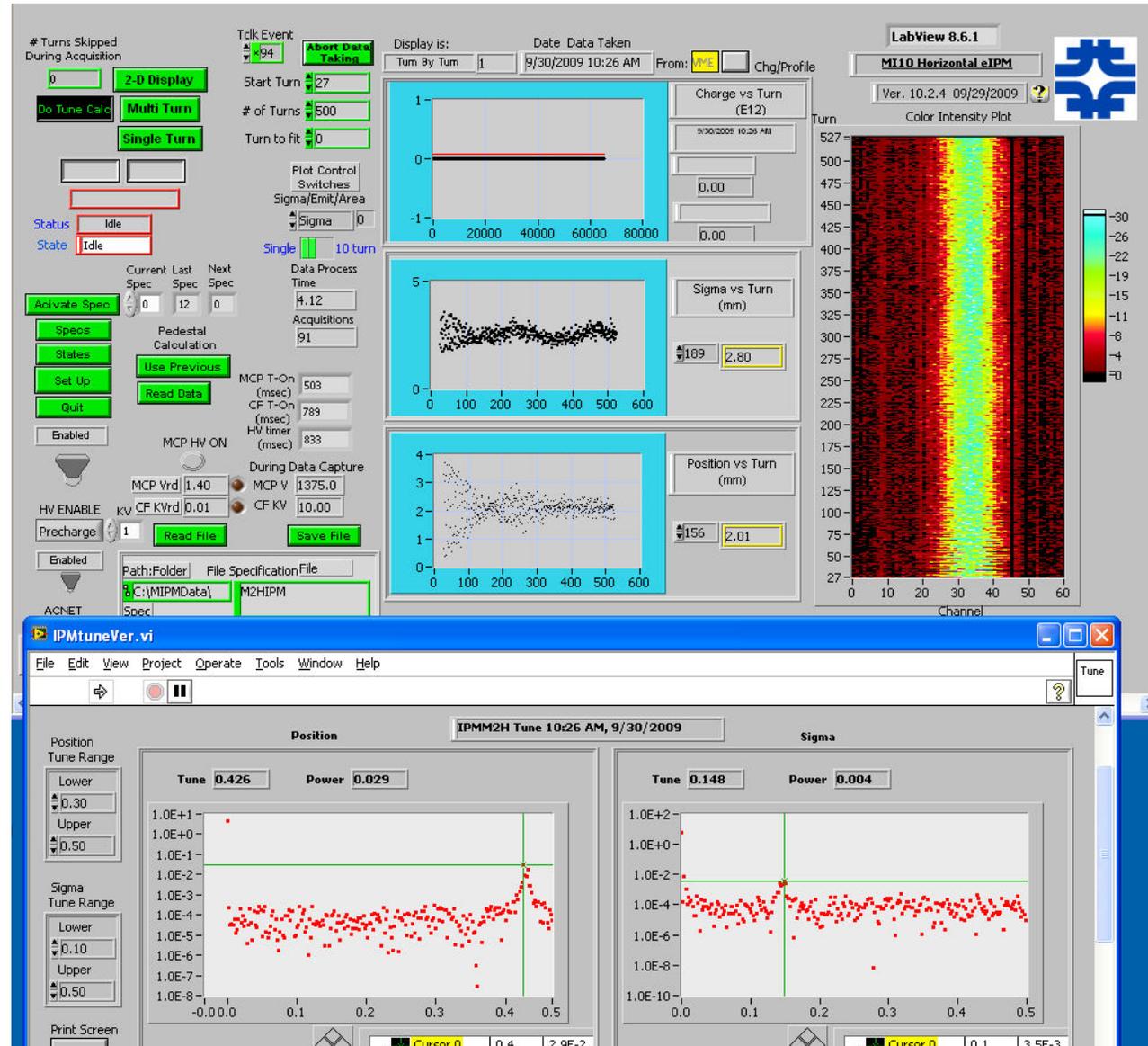
# IPM Measurement New Features

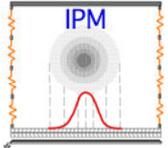
- New Main Injector
  - Higher speed 16 channel digitizers 80MHz
    - multiple sample each batch for better accuracy/sample
    - Allows for digital filtering of signals on A/D
  - 96 Channels to be sampled using new Brian Fellenz 20 channel preamp module.
  - Control Grid to gate off electrons for unmeasured batches
    - Should significantly increase MCP life time.
  - 2000 samples at either
    - 1 Batch per revolution
    - Spread across all batches for about 300 turns



# Typical Data Display

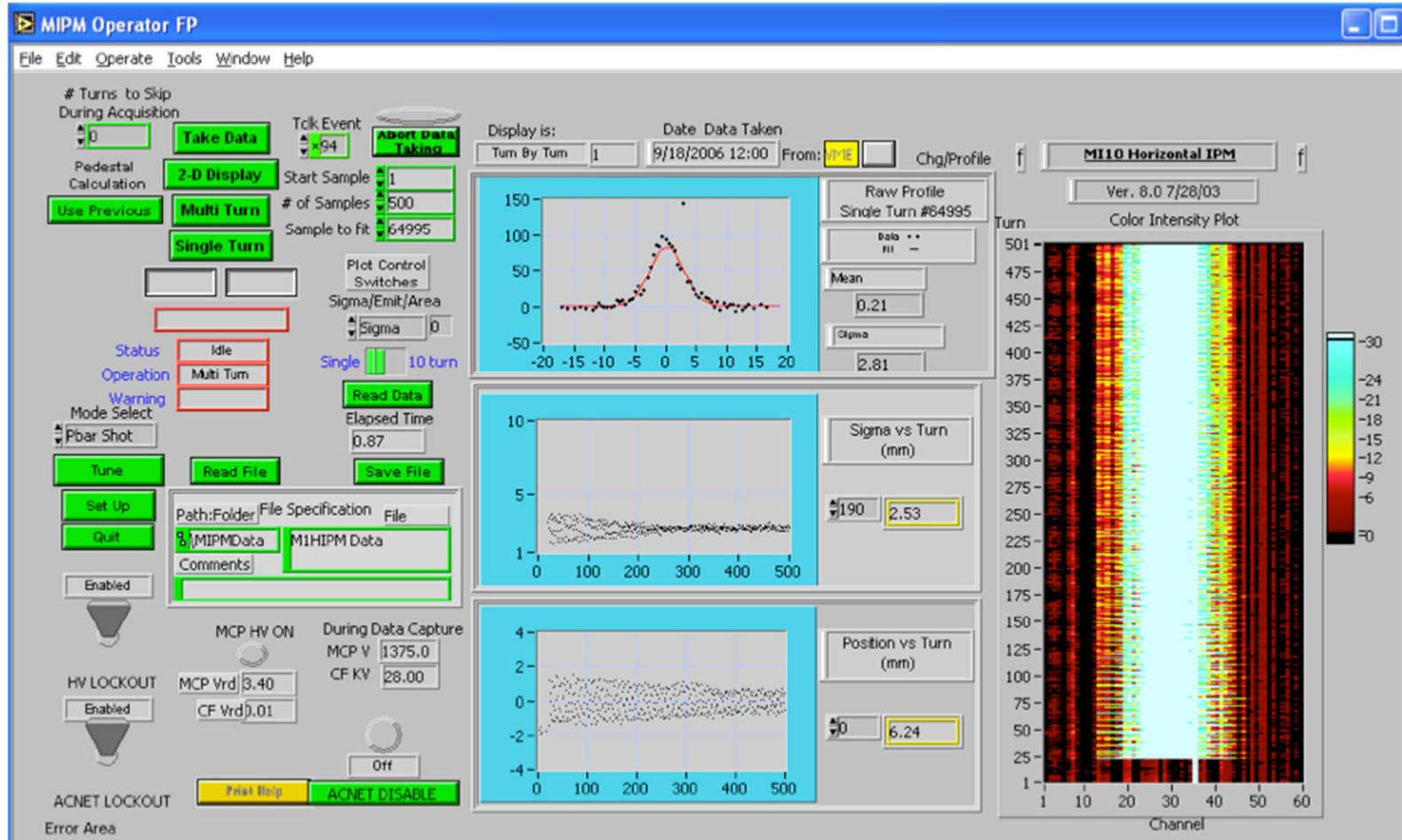
Main Injector:  
Injection tuning study.  
Showing injection  
oscillations for the first  
300 turns.

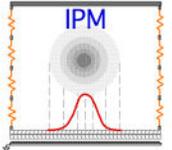




# Typical Data Display cont'd

Main Injector  
P-Bar injection  
tuning.



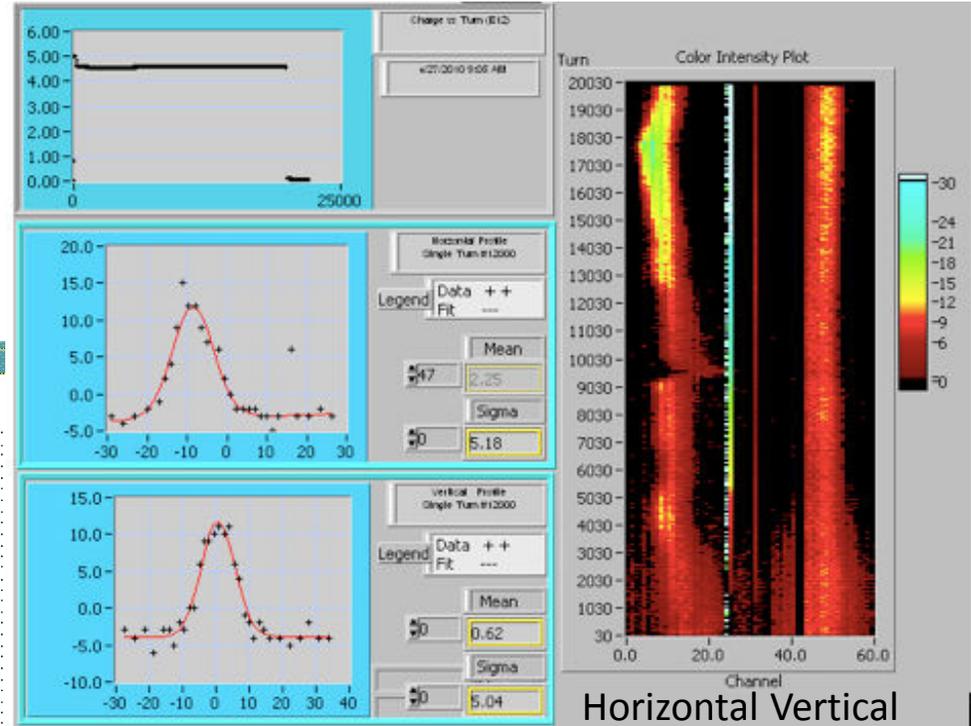
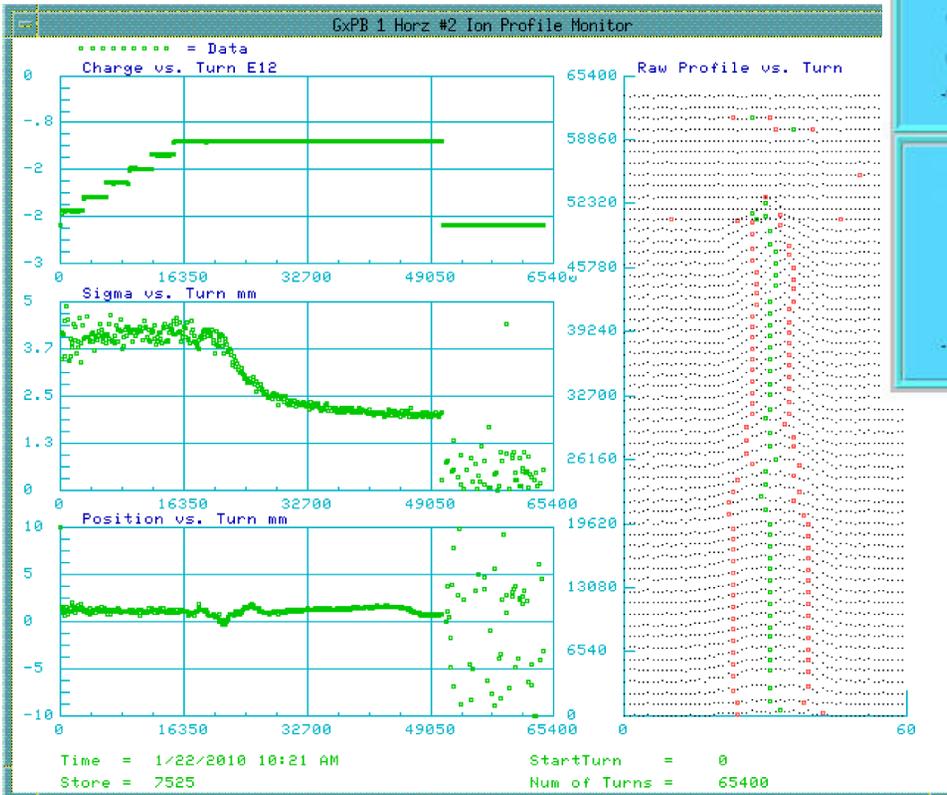


# Typical Data Display

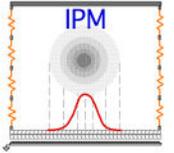
Last

## Booster LabView Front End

### Main Injector Console Application

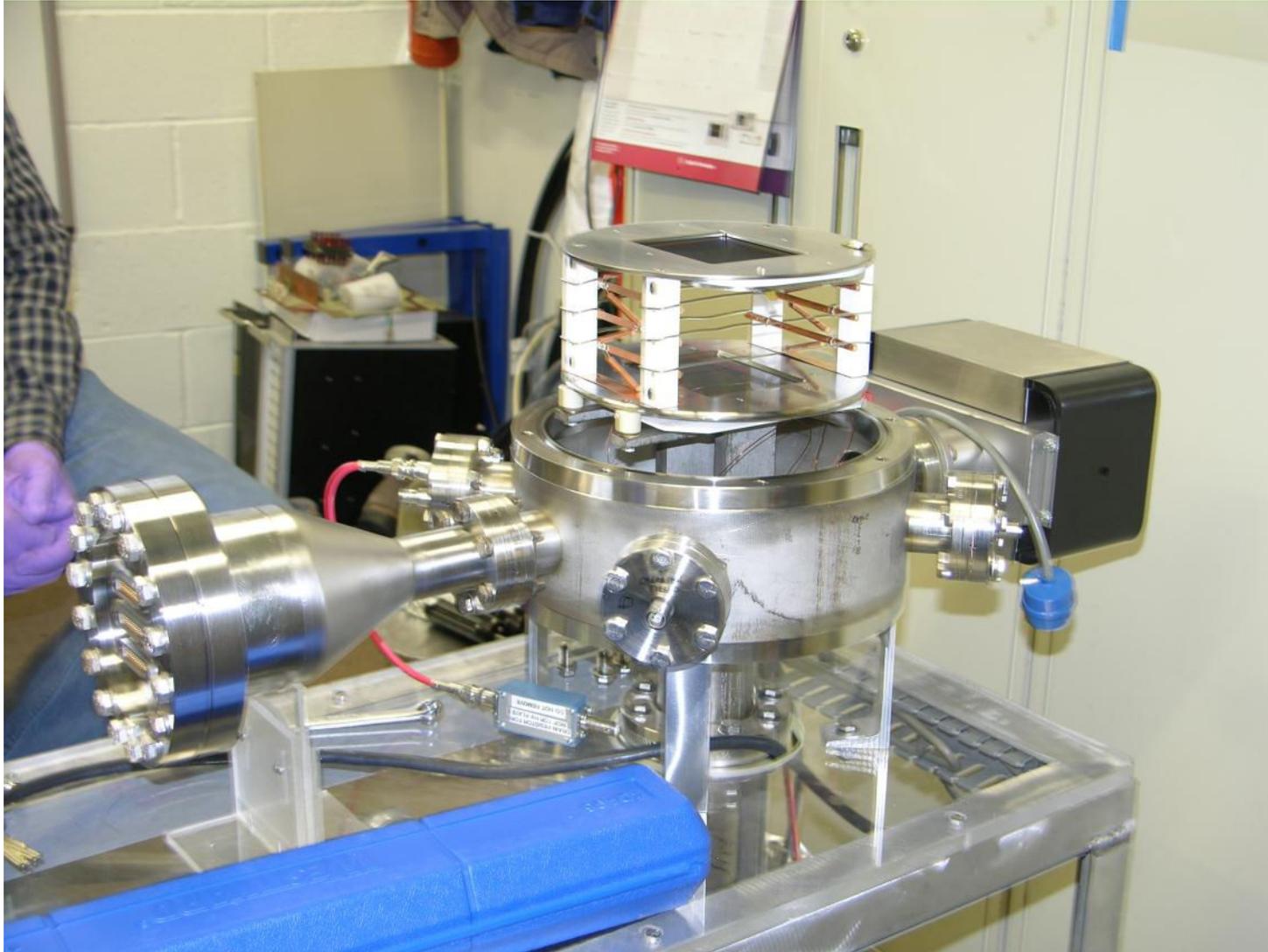


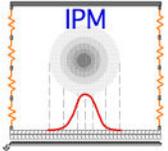
Top left trace indicates intensity.  
 Bottom left 2 plots –  
 can plot sigma and position,  
 or individual turn profiles.



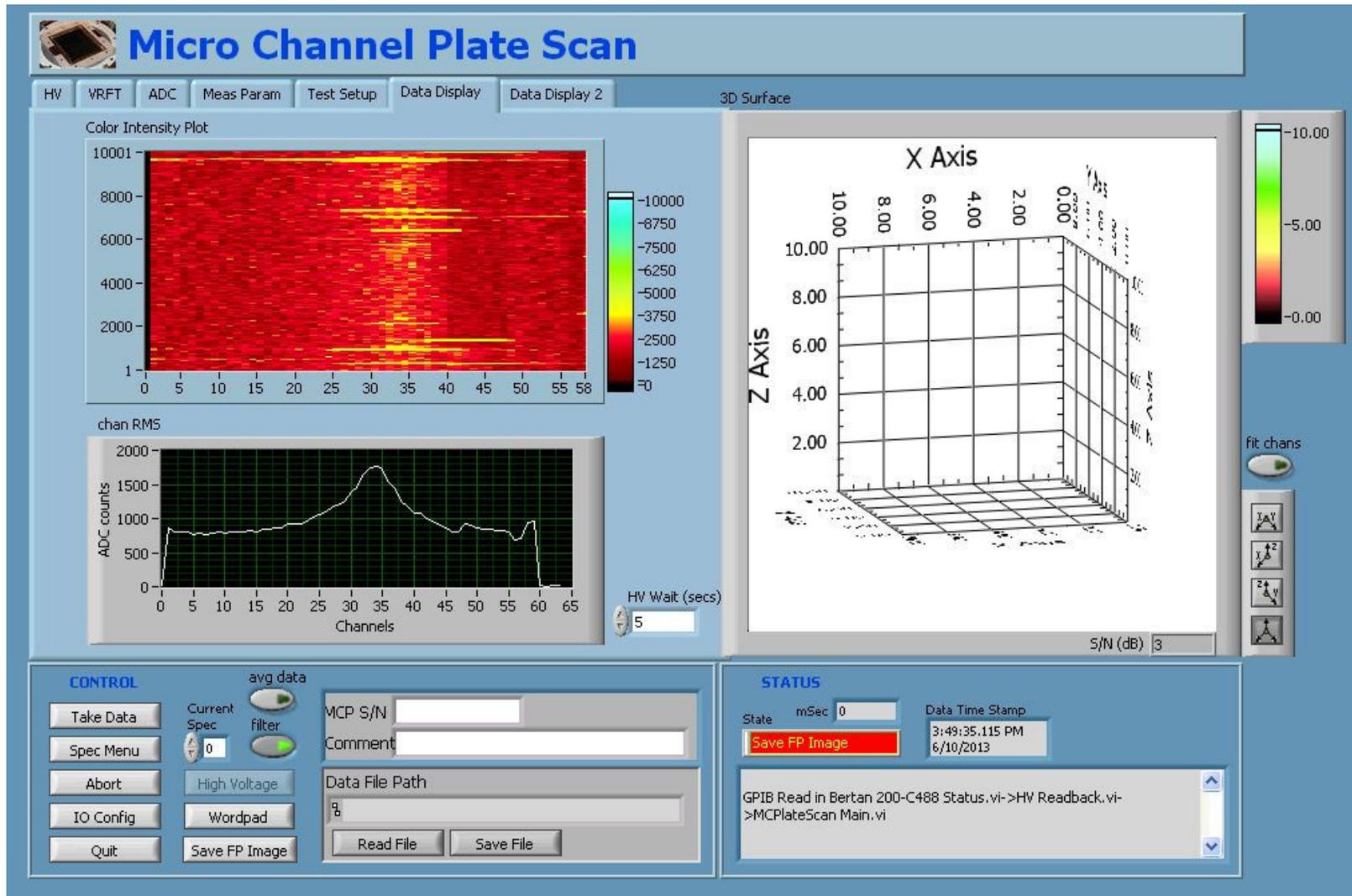
# MCP Test Chamber

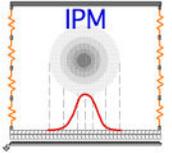
- Facility to scan MCPs for suitability and look at areas of reduced gain





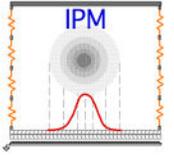
# Test Chamber Measurements





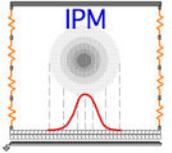
# The Players

- Instrumentation
  - Dave Slimmer, Carl Lundberg, Jim Galloway, Brian Fellenz, Dan Schoo, John VanBogaert, Alexei Semenov
- Main Injector, etc...
  - Bruce Brown, Denton Morris, Jim Volk
- Mechanical Support
  - Matt Alvarez, Tom McLaughton, Dave Tinsley, Kevin Duel, Linda Valerio, Eric Pirtle, Jim Wilson, James Williams, Sali Sylejmani, Scott McCormick, Debbie Bonifas, Tom Lassiter
- Technical Division
  - David Harding, Oliver Kiemschies, Vladimir Kashikhin, Bill Robotham, Michael A. Tartaglia, Mark D Thompson, Gueorgui Velev, Dana Walbridge



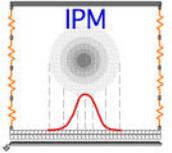
# Intermission





# Gated IPM Concept

- Problem with MCP is short lifetime
  - Plate is using up lifetime whenever beam is in the machine and the IPM voltage is on
  - Voltage takes a while to raise and lower
- Would like to be able to gate the charge to preserve the MCP
  - Stop the electrons and ions from reaching the MCP
  - Allow the electrons and ions an escape path from the IPM active region
    - i.e. no Penning traps

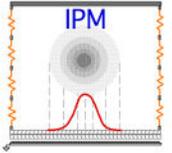


# Gated IPM Concept

- The force on a charged particle is

$$\vec{F} = q \left( \vec{E} + \frac{\vec{v}}{c} \times \vec{B} \right) = m \frac{d\vec{v}}{dt}$$

- Assume that  $\vec{E} = E_0 \hat{x}$  and  $\vec{B} = B_0 \hat{y}$
- The solution to this is circular motion in the  $\hat{x} - \hat{z}$  plane, constant motion along  $\hat{y}$  and a drift along  $\vec{E} \times \vec{B}$  which in this case is  $\hat{z}$ , i.e. along the beam
- Putting in the values for the electric and magnetic fields gives us a drift velocity of  $\sim 10 \text{ cm}/\mu\text{s}$  along the proton beam direction
  - The electrons will have drifted beyond the MCP in  $\sim 1-2 \mu\text{s}$



# MATLAB Simulation

- Simulation tracks particles through arbitrary E and B fields
- Uses interpolation to obtain the fields at any point from previously calculated field distributions
- Propagates using a relativistic formula

$$\mathbf{F}(\mathbf{r}, t) = \frac{d\mathbf{p}}{dt} = m \frac{d\tilde{\gamma}\mathbf{v}}{dt}$$

$$= m \left( \mathbf{v} \frac{d\tilde{\gamma}}{dt} + \tilde{\gamma}\mathbf{a} \right)$$

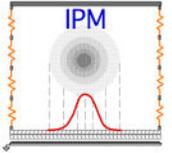
$$\mathbf{F}(\mathbf{r}, t) = m\tilde{\gamma} \left( \mathbf{a} + \tilde{\gamma}^2 \tilde{\boldsymbol{\beta}} (\tilde{\boldsymbol{\beta}} \cdot \mathbf{a}) \right)$$



$$\mathbf{a} = \frac{1}{\tilde{\gamma}m(1 + \tilde{\gamma}^2 \tilde{\boldsymbol{\beta}}^2)} \left[ \mathbf{I} + \tilde{\gamma}^2 (\tilde{\boldsymbol{\beta}}^2 \mathbf{I} - \tilde{\boldsymbol{\beta}} \tilde{\boldsymbol{\beta}}^T) \right] \mathbf{F}$$

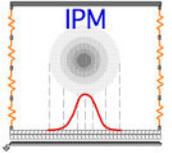
$$= \frac{1}{\tilde{\gamma}m} \left[ \mathbf{I} - \frac{\tilde{\gamma}^2}{(1 + \tilde{\gamma}^2 \tilde{\boldsymbol{\beta}}^2)} \tilde{\boldsymbol{\beta}} \tilde{\boldsymbol{\beta}}^T \right] \mathbf{F}$$

$$\mathbf{a} = \frac{1}{\tilde{\gamma}m} \left[ \mathbf{I} - \tilde{\boldsymbol{\beta}} \tilde{\boldsymbol{\beta}}^T \right] \mathbf{F}$$



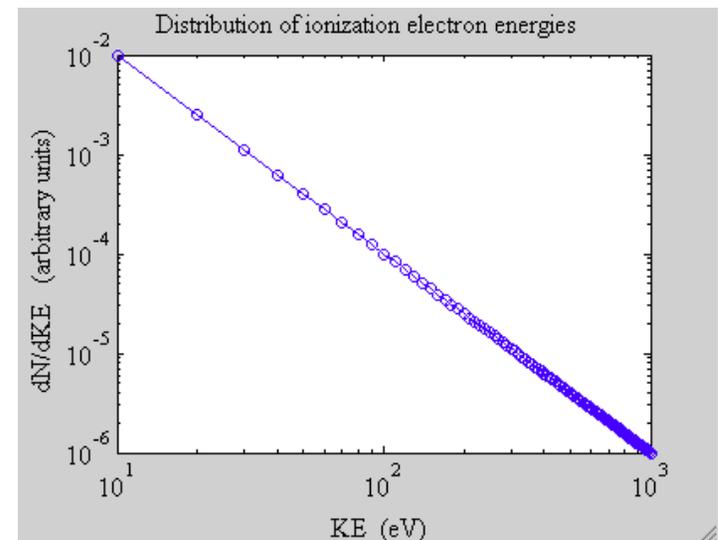
# Matlab Simulation

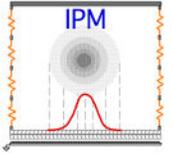
- Once the acceleration is determined, a discrete evaluation of the differential equation of motion is used to step the particles
- The magnetic and electric fields are handled separately
  - Magnetic contribution to the motion is only applied to the components perpendicular to the B field
  - Magnitude of the velocity perpendicular to the B field is forced to be preserved, since the B field does no work
    - This in particular helps with the tight spirals along the field lines



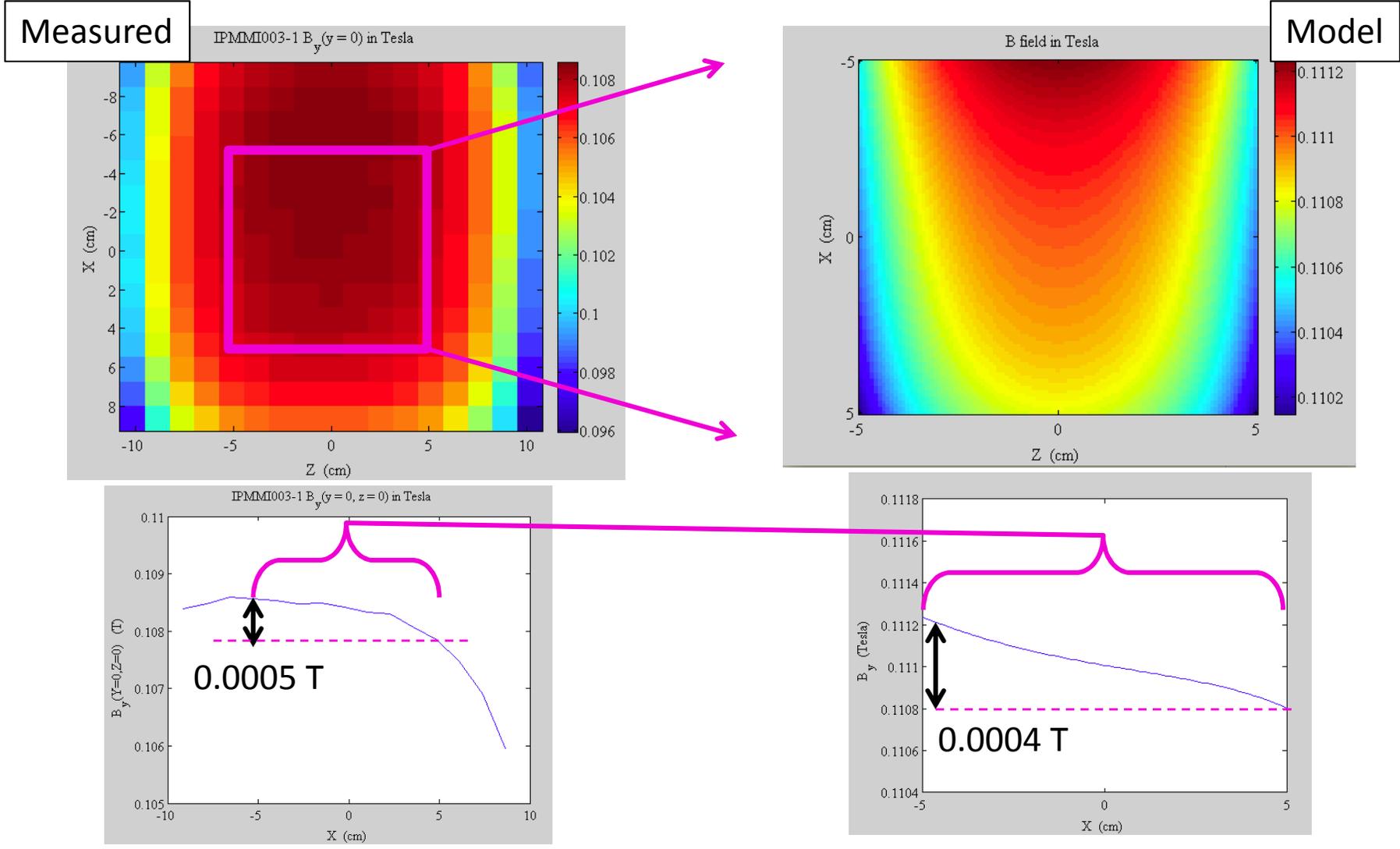
# Matlab Simulation

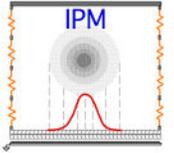
- The electric and magnetic fields of the bunch are calculated before hand for various bunch parameters
  - Shifted as a function of time to represent the moving beam
- Electric field of IPM from a 2-D Poisson calculation
- Magnetic field from 3-D magnet model
- Ionized particle distributions are random in emission angle with  $1/E^2$  energy distribution →



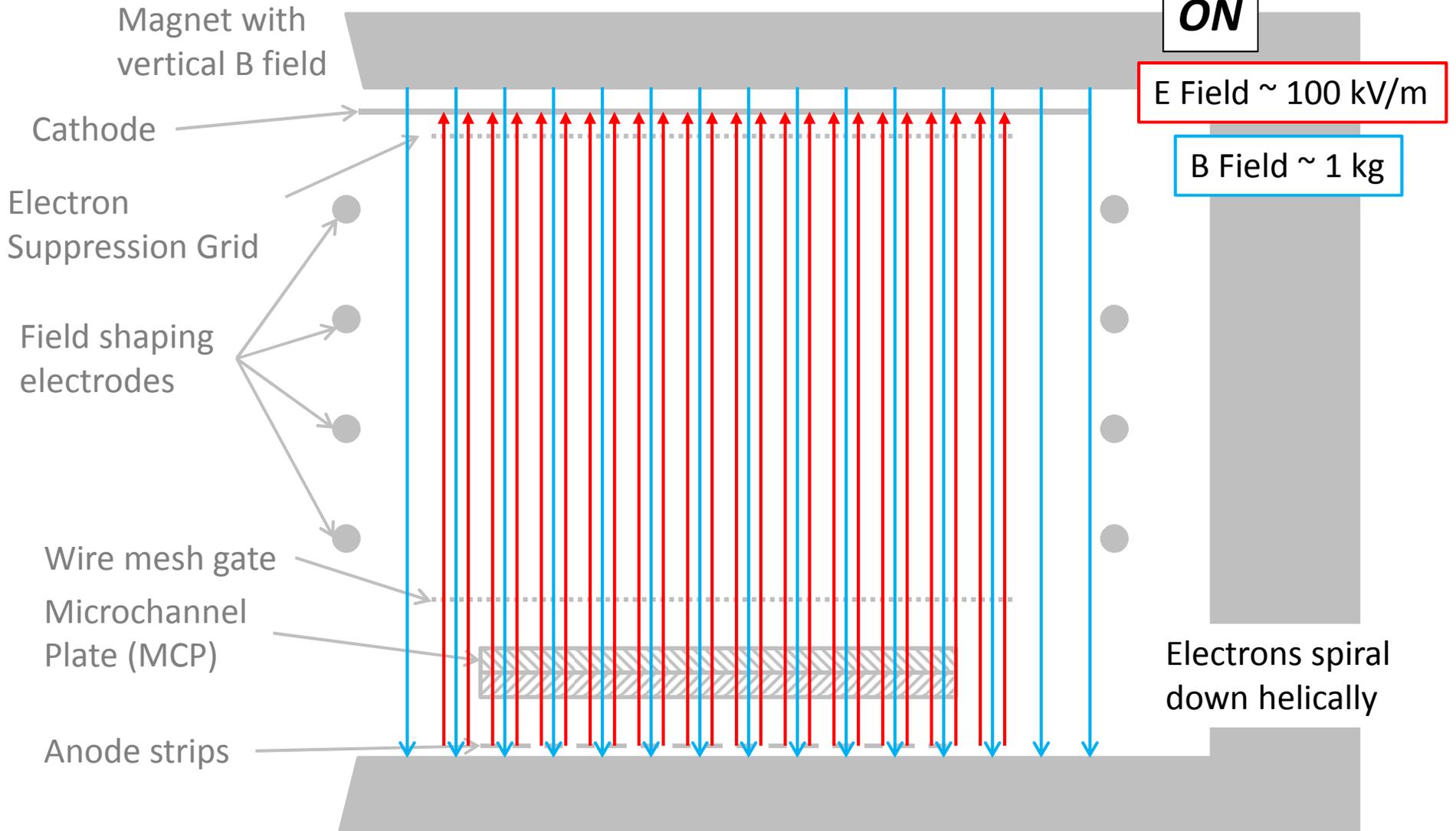


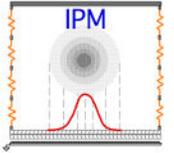
# Magnetic Field in Simulation





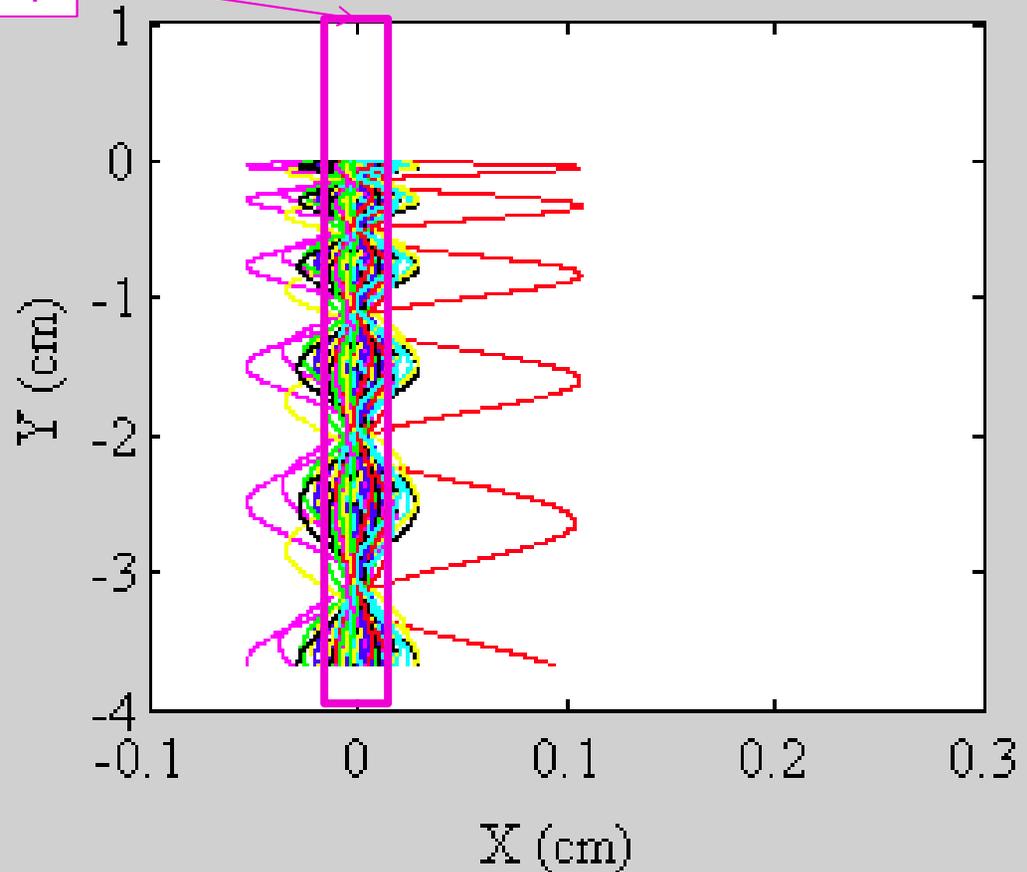
# Gated-on IPM





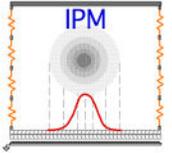
# Gated-on IPM

Anode Strip



Particles originating  
from single point  
(resolution contribution)

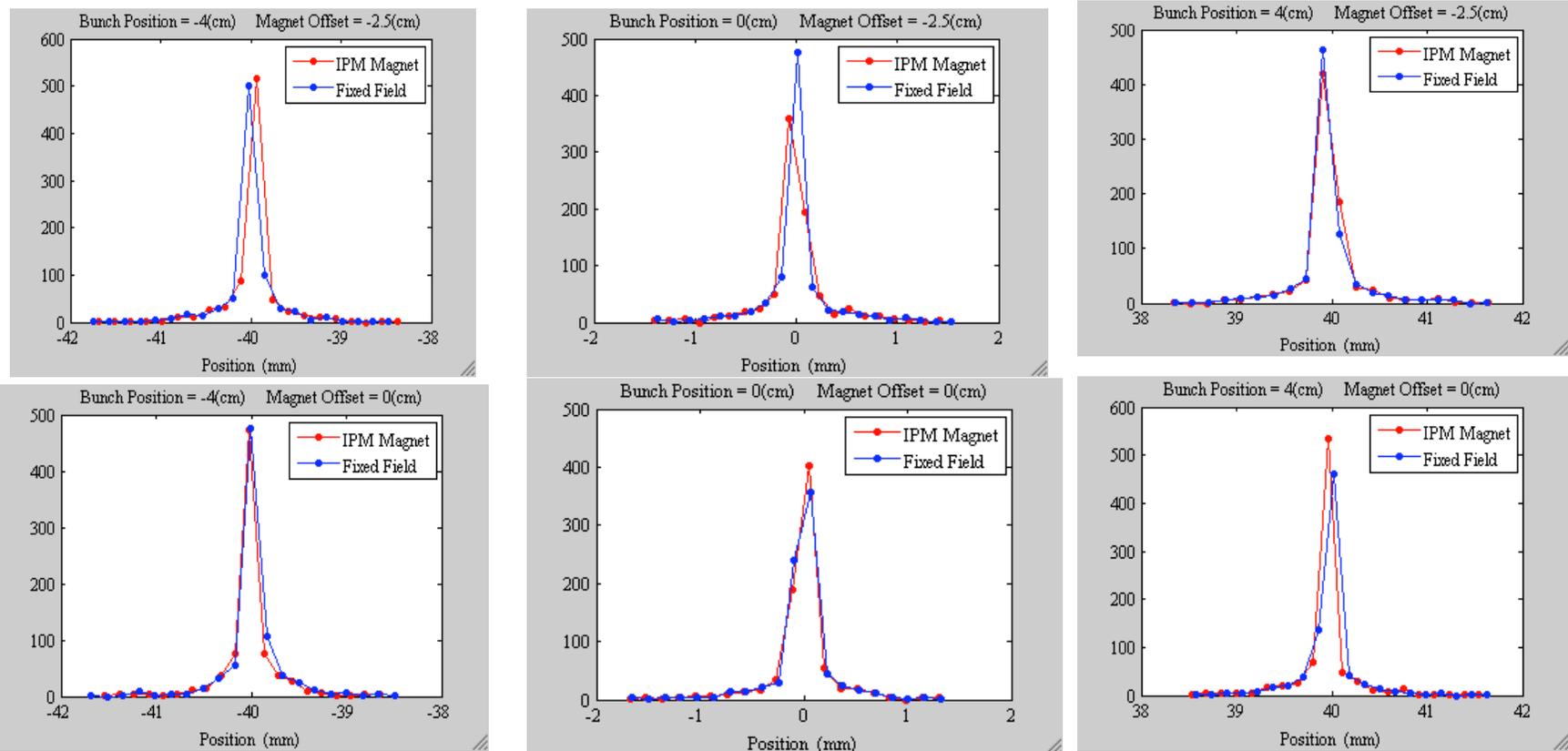
Elapsed time  $\sim 1.7$  ns

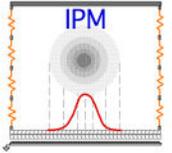


# Gated-on IPM

Particles originating from single point  
(resolution contribution)

Bunch offset refers to x





# Gated-on Expected Signal

- From figure 7 of Sauli #, the number of primary ion pairs produced in one centimeter of a gas species  $i$  at one atmosphere of pressure by one minimum ionizing particle can be roughly parameterized as

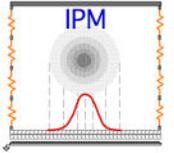
$$n_i \approx \frac{3}{2} Z_i$$

- Expressing this in terms of the proton bunch parameters and partial pressures in the beampipe one arrives at

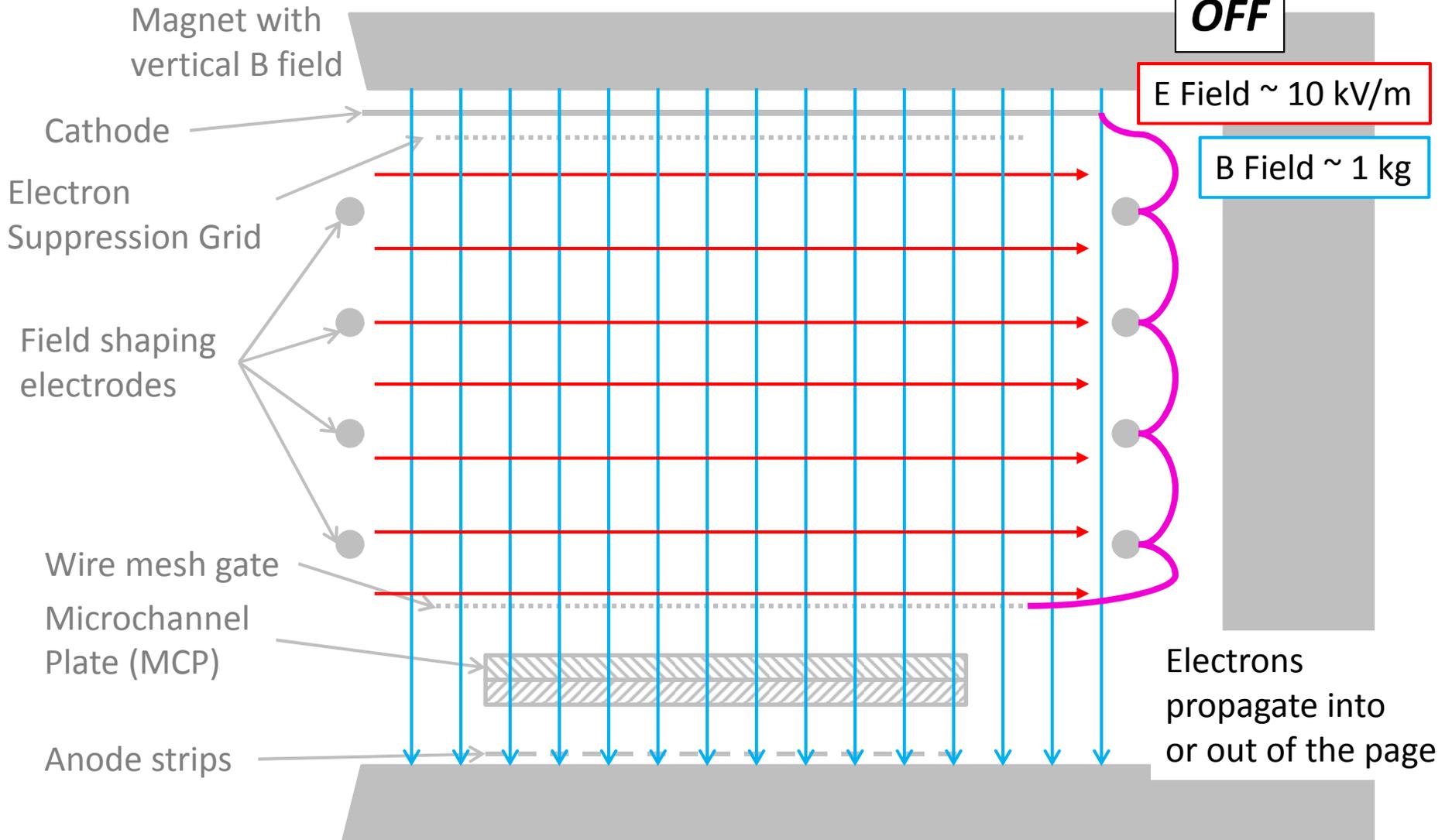
$$n_j(t) \approx \frac{QL\delta}{500e\sigma_T\sigma_t2\pi} \left[ e^{-\frac{(j\Delta)^2}{2\sigma_T^2}} \right] \left[ e^{-\frac{t^2}{2\sigma_t^2}} \right] \sum_i Z_i P_i$$

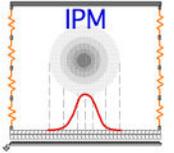
- At the peak of a Main Injector bunch, the number of ionization electrons is **~10** per anode strip (no MCP gain)

#F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers", CERN 77-09, 3/5/77.



# Gated-off IPM

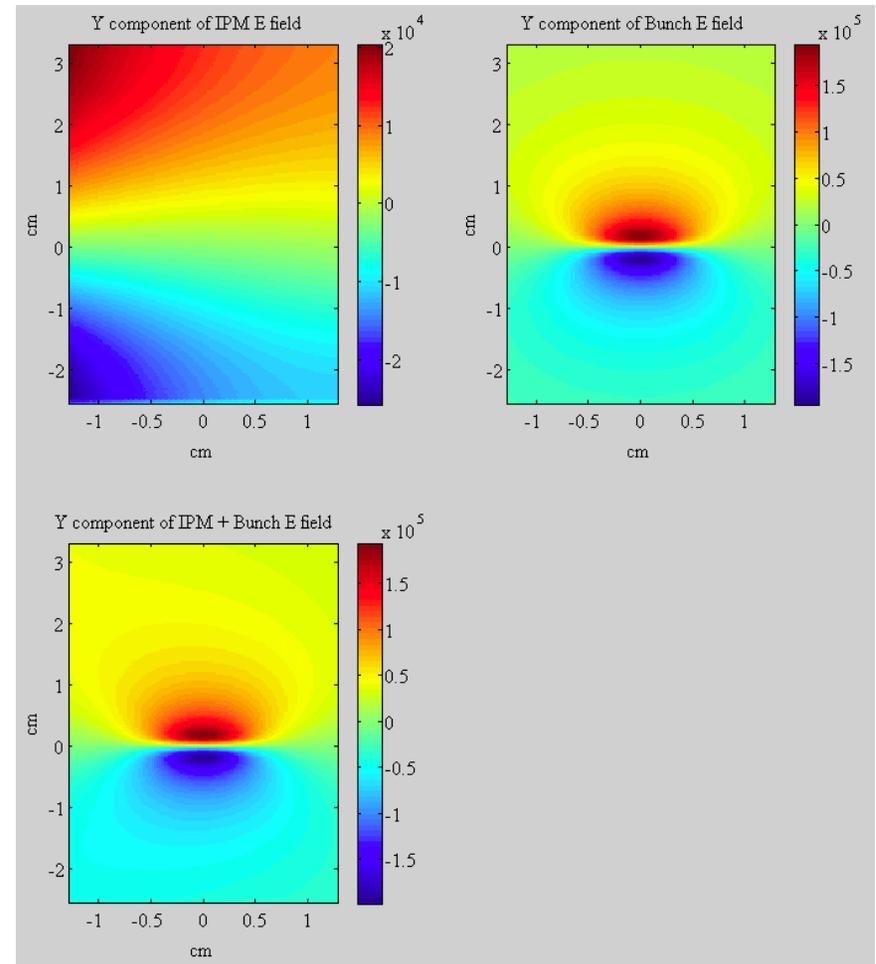
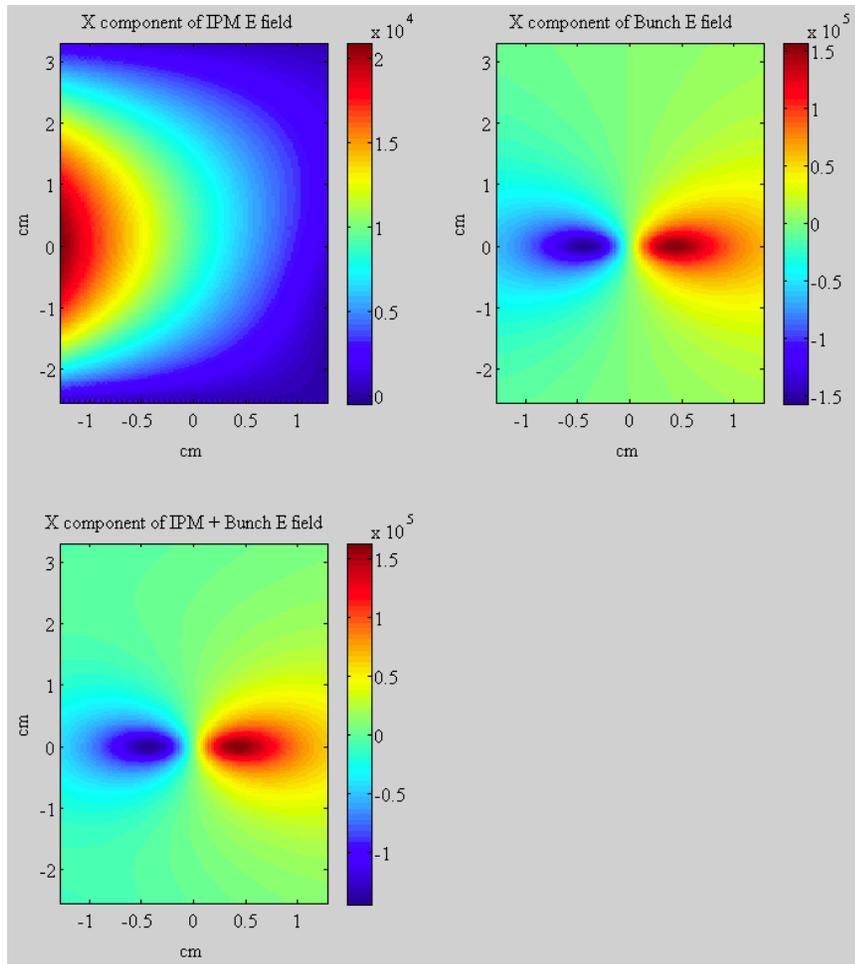


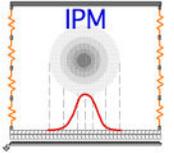


# Gated-off Fields

X Component of E field

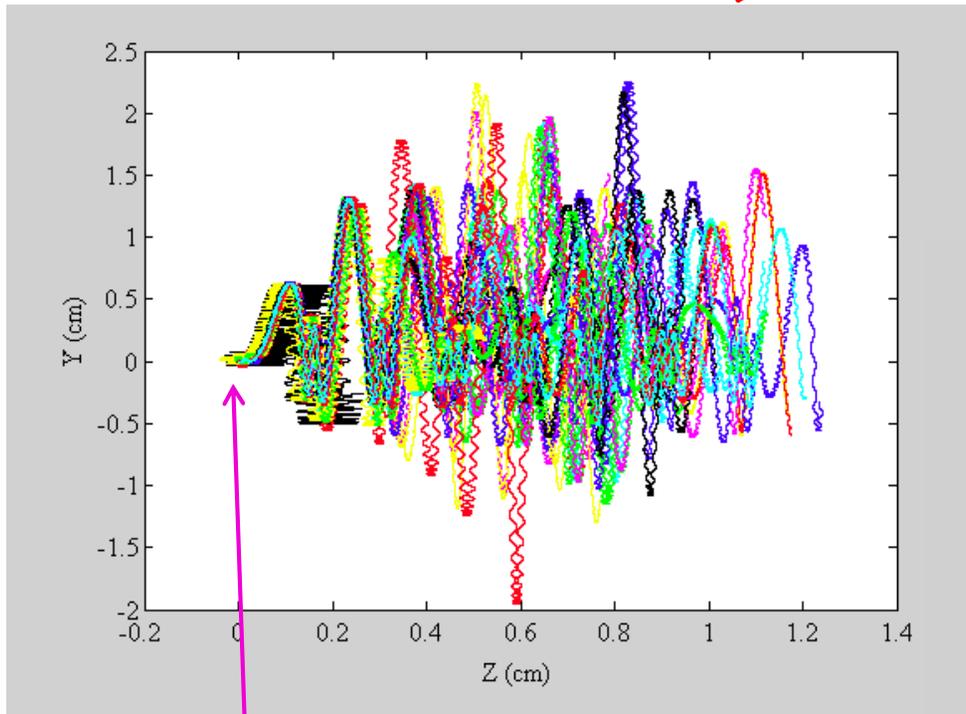
Y Component of E field





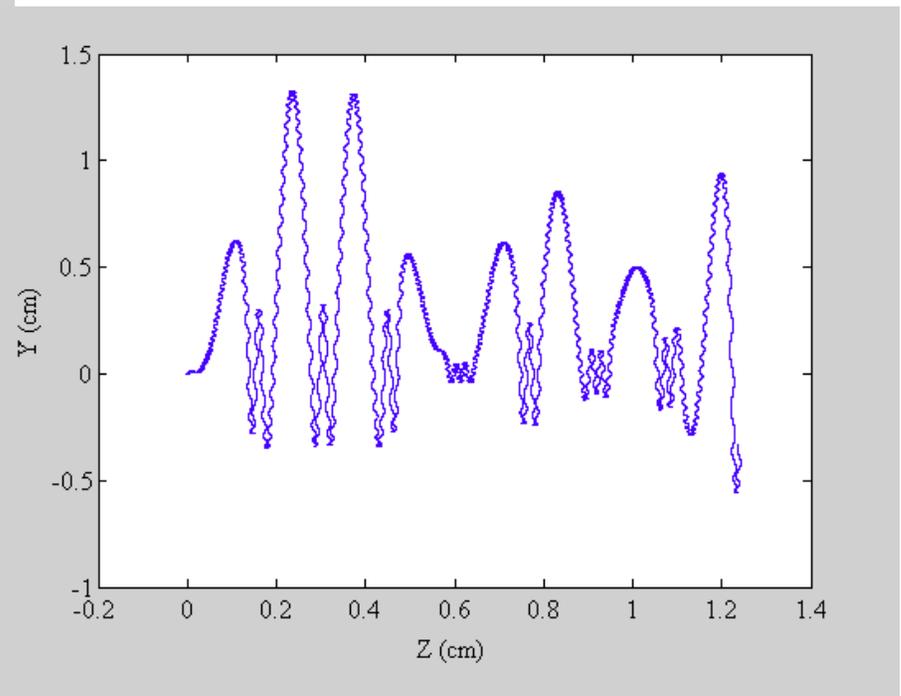
# Gated-off Motion

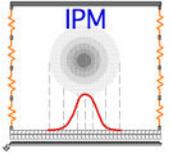
Electrons drift along beam direction



Particle origination point

Single particle

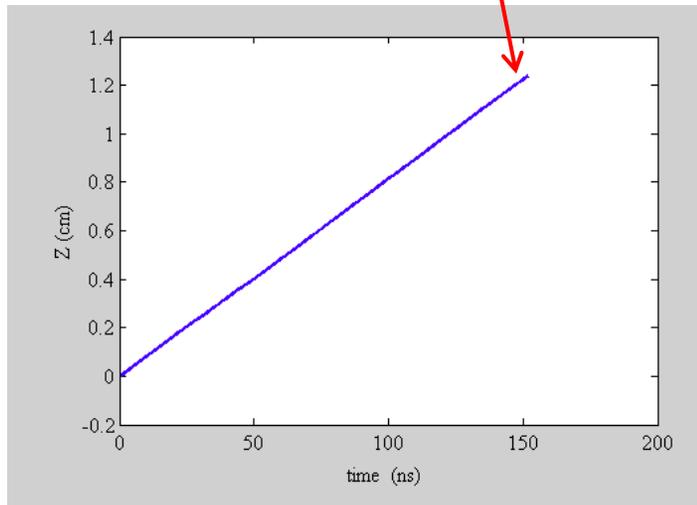




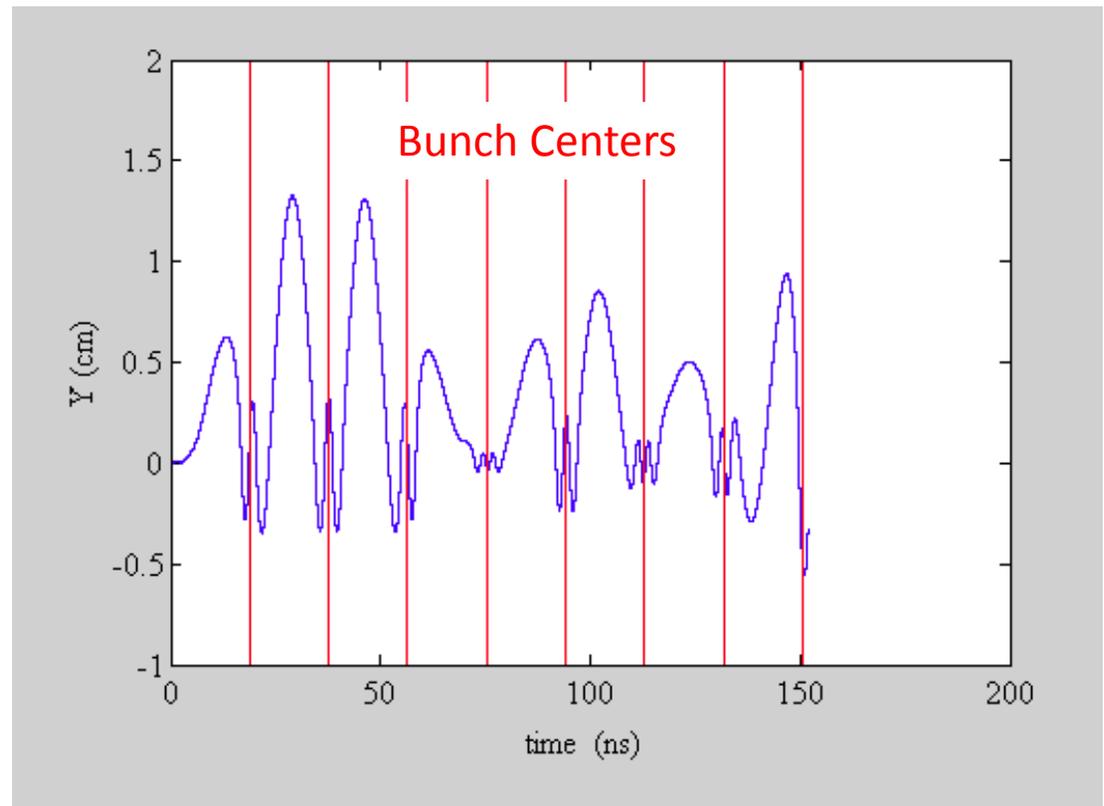
# Gated-off Behavior

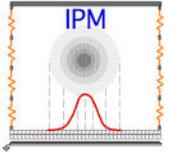
*What happens when electrons reach the end of the field region?*

Drift Velocity  
 $1.2 \text{ cm} / 150 \text{ ns} = 8 \text{ cm}/\mu\text{s}$   
 Compared to  
 $10 \text{ cm}/\mu\text{s}$  analytically  
 estimated



Y motion vs time

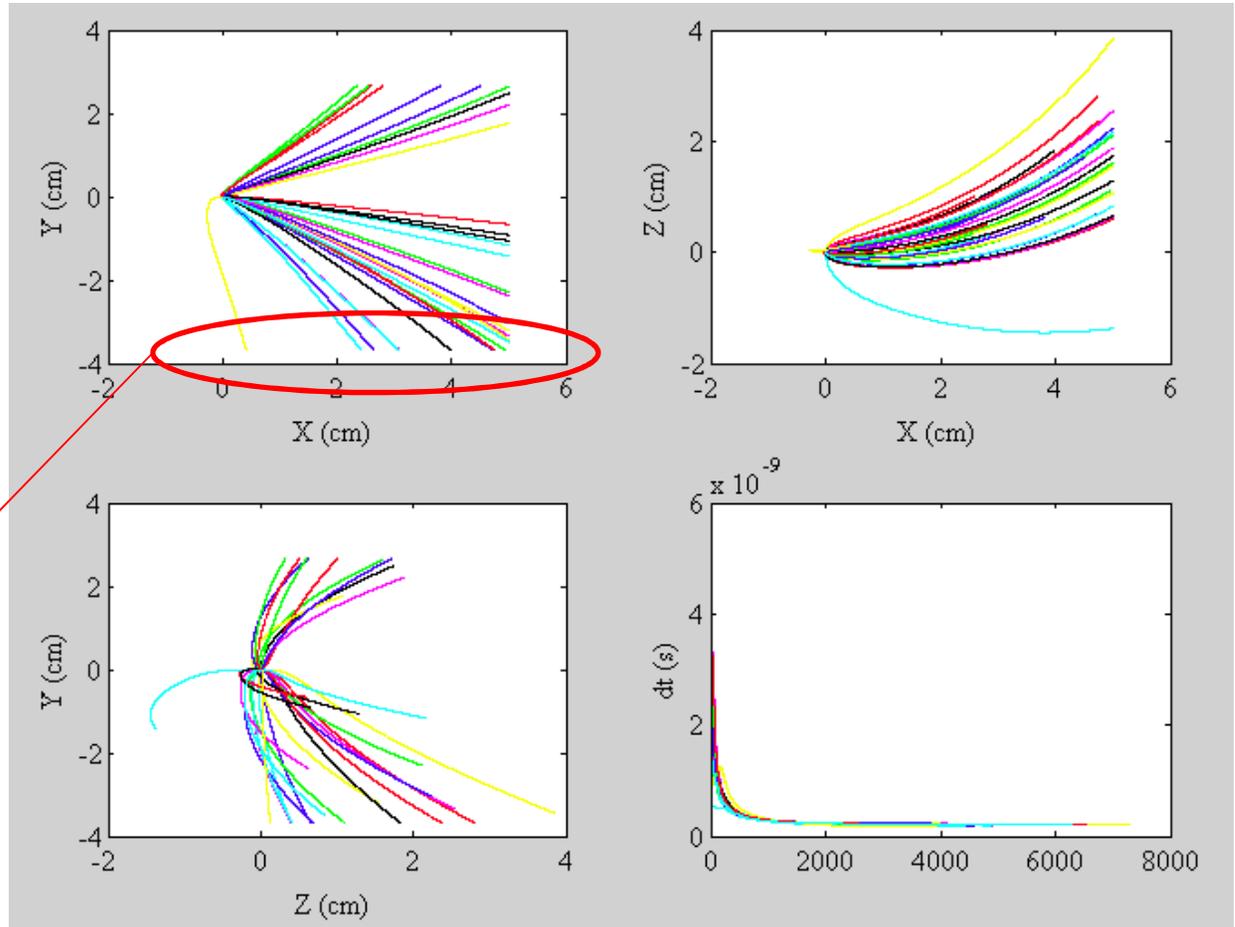




# Gated-off Ion Paths

Elapsed time is  $\sim 1.5 \mu\text{s}$

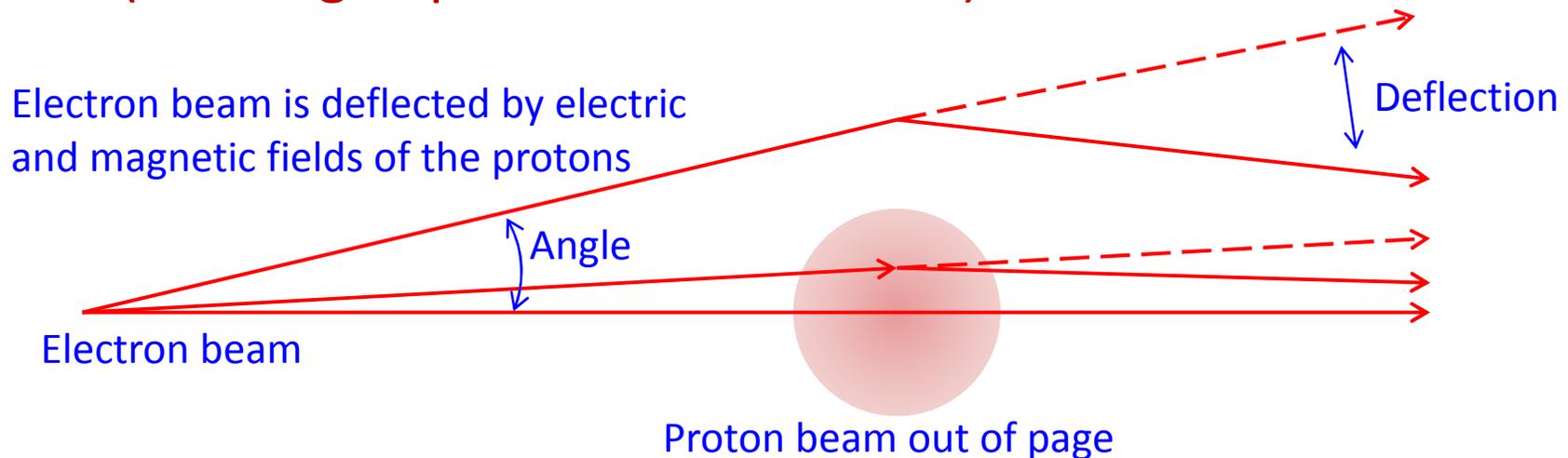
Initially appears ok, since ions do not go much beyond the gating grid  
 -- However --  
 Secondaries from ion impacts on gating grid could be a problem





# Electron Beam Profiler

- Increasing beam power in MI/RR implies the need for non-invasive instrumentation
  - Electron beam deflection technique is one choice (working implementation at SNS)



- Deflection vs. Angle provides information about the proton beam transverse profile



# Techniques for Main Injector

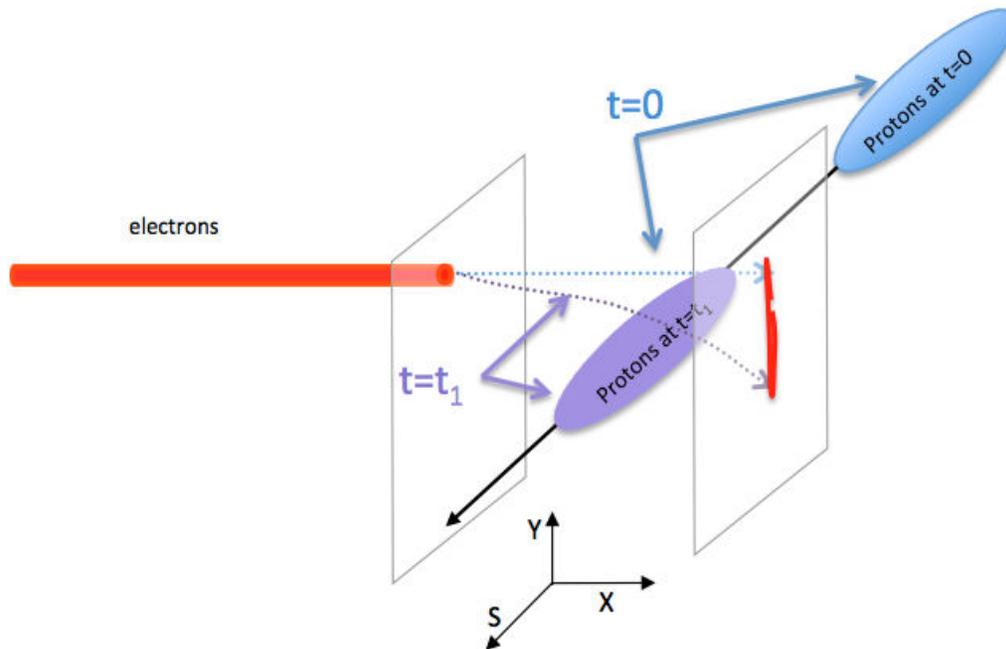
- Various techniques for measuring deflection
  - Fast scan through peak of bunch (similar to SNS)
    - Requires fast deflector ( $< 1$  ns sweep time)
  - Slow scan, akin to flying wires (most likely solution for Nova)
    - Position the beam and record the maximum deflection as the beam passes by
      - Leave the electron beam stationary
      - Sweep the beam along the proton direction
        - » Obtain longitudinal distribution
- Collaborating with Wim Blokland at SNS who has done simulations of the various techniques



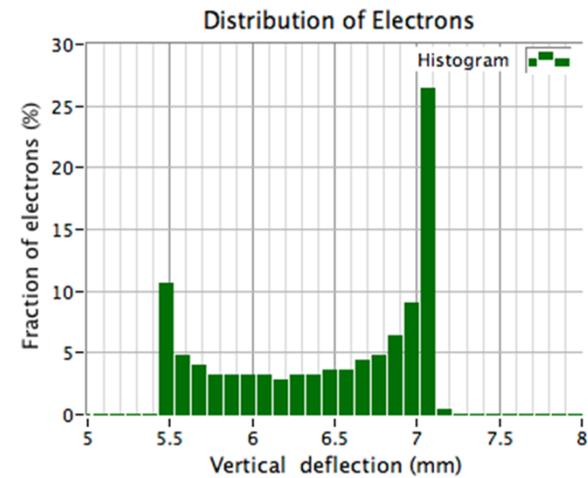
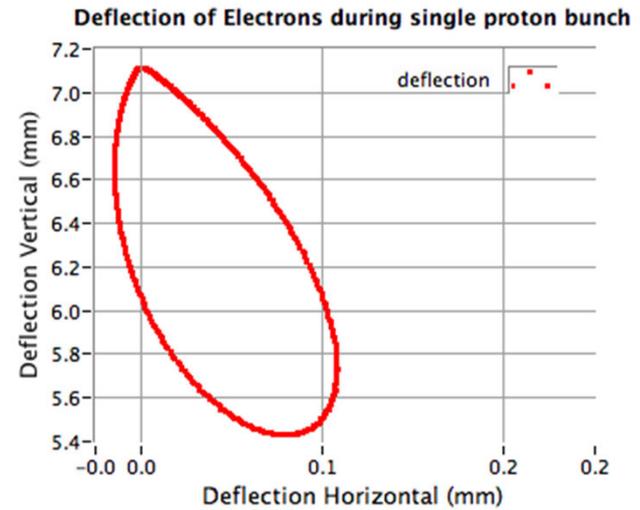
# Electron Deflection

## Slow electron sweep

- Position the electron beam
- Record the deflection of a bunch
- Move the electron beam and repeat



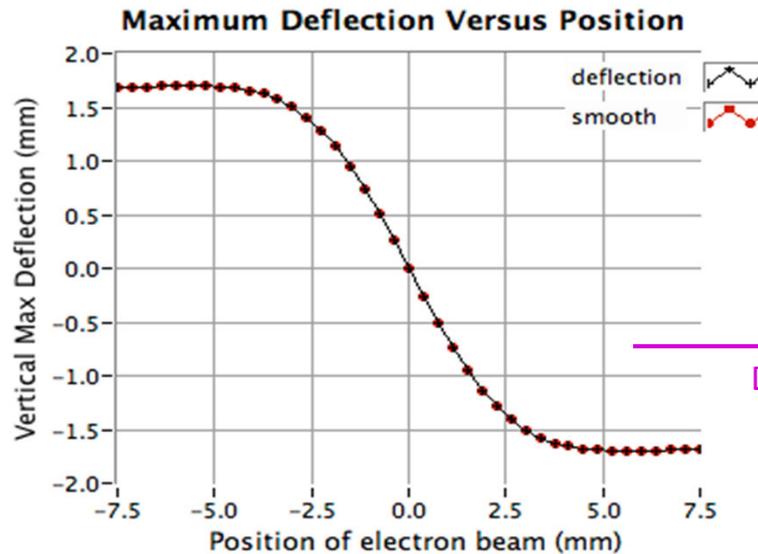
Plots courtesy of Wim Blokland



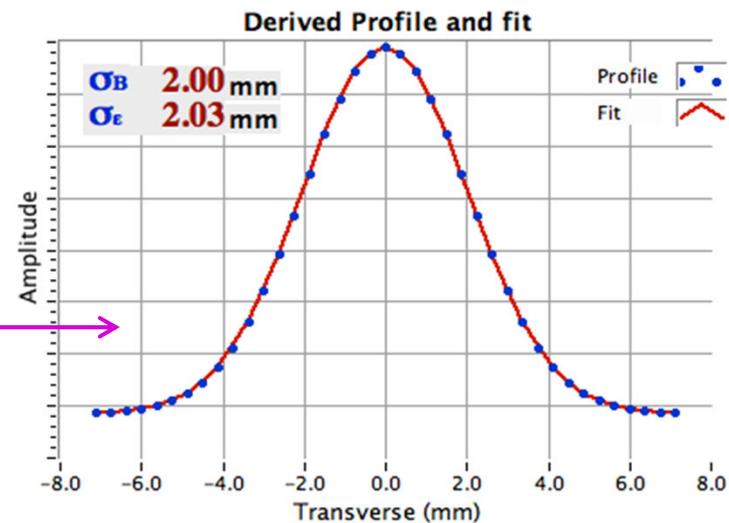


# Electron Deflection Simulation

- Step the electron beam through the proton beam and record maximum deflections
- Derivative of deflection vs. position is nominally beam profile



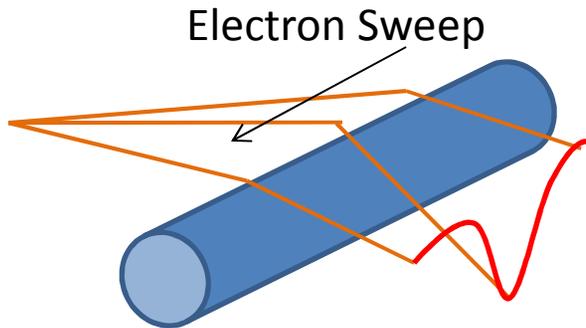
Derivative



Plots courtesy of Wim Blokland

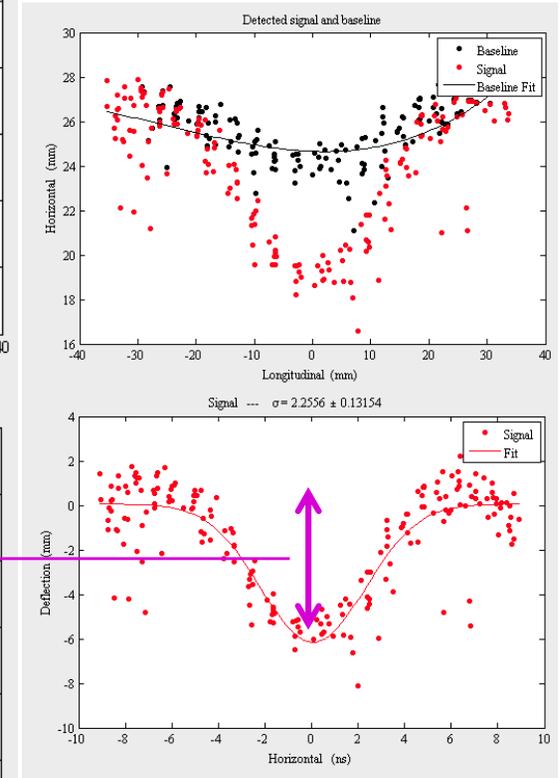
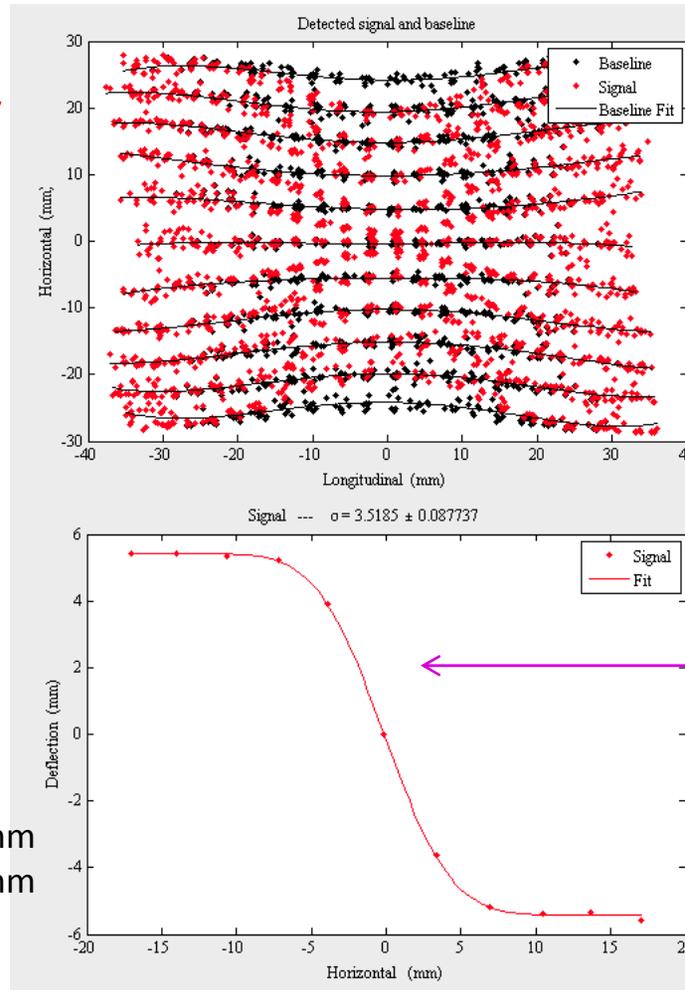


# Alternative Deflection Scheme



- Sweep the electron beam along the proton bunch
- Sweep duration coincides with the duration of the proton bunch

Beam Simulated Transverse  $\sigma = 3$  mm  
 Meas. Simulated Transverse  $\sigma = 3.5$  mm

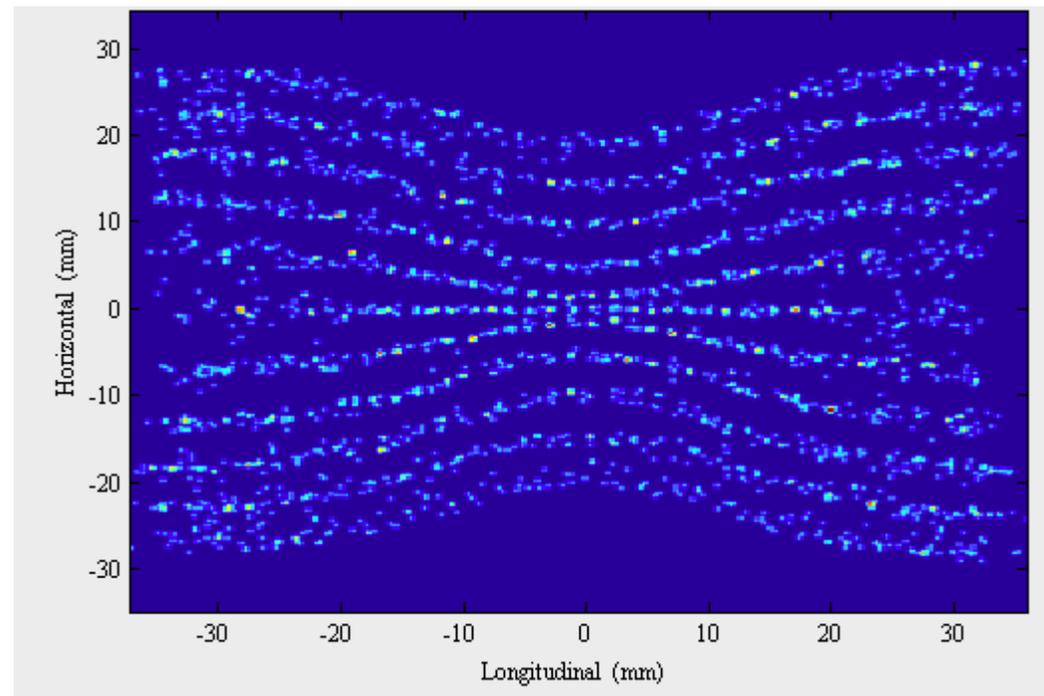


Beam Sim. Longitudinal  $\sigma = 2$  ns  
 Meas. Sim. Longitudinal  $\sigma = 2.3$  ns



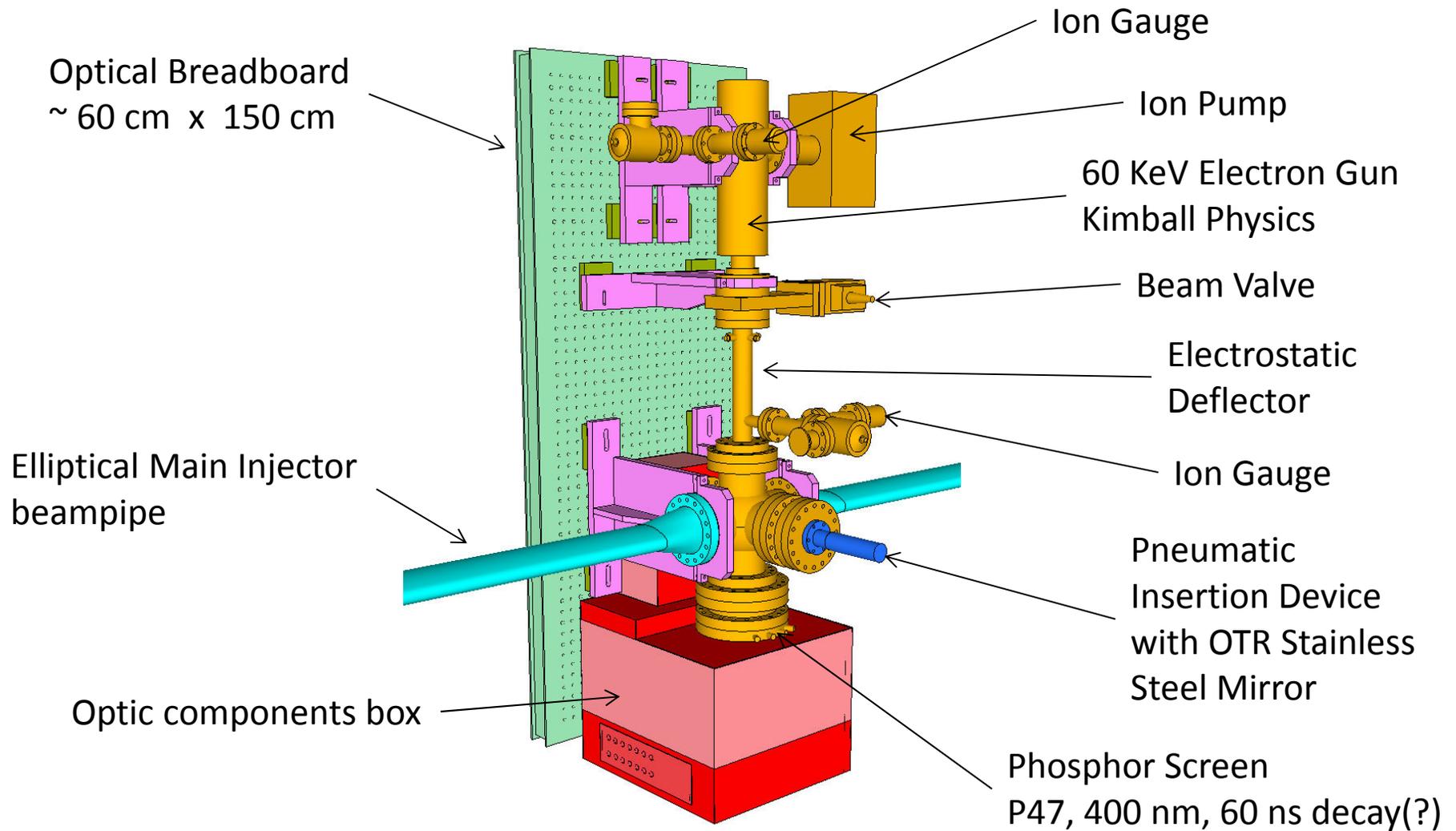
# Simulated Camera Image

- Camera frames are  $\sim 30$  ms
- Main Injector cycle is  $\sim 1$  s
- Need to step many times per frame to accumulate data fast enough for measurement
  - Complicated to extract each step





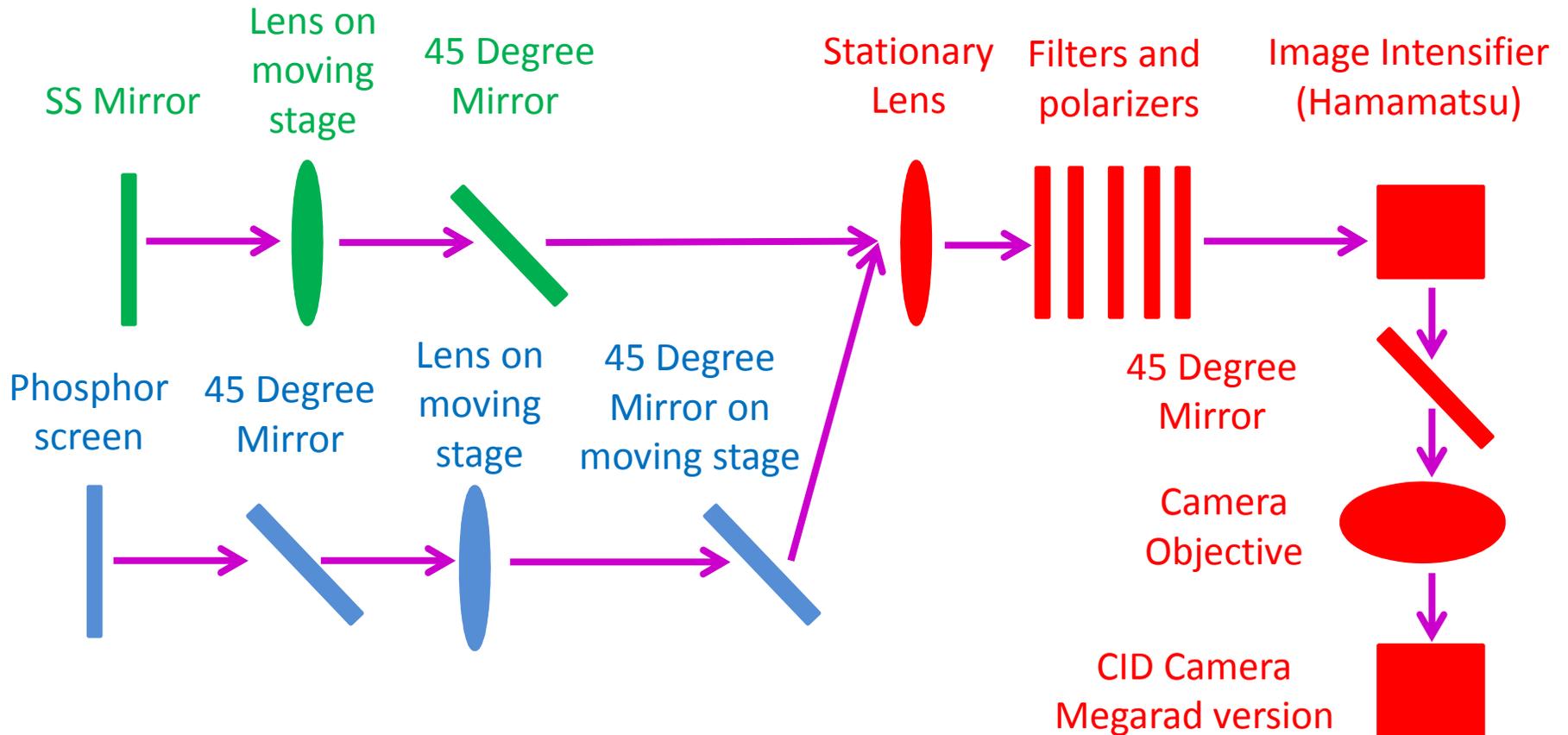
# Electron Beam Device





# Optics

Two optical paths: **OTR screen** and **Phosphor screen** with some **shared elements**  
 OTR screen is inserted at location of proton beam (sans proton beam) and used to focus the electron beam and measure the electron beam spot size

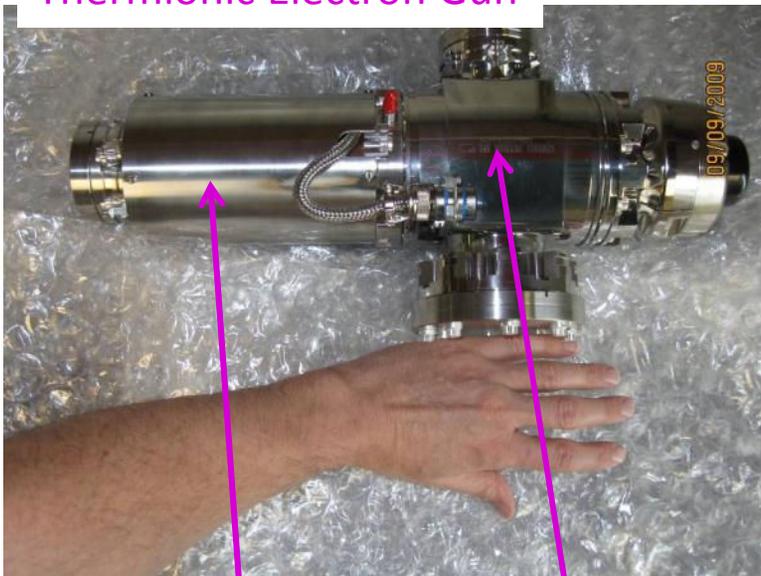


# Devices

Kimball Physics up to 60 KeV  
(we will use up to 15 KeV)  
6 mA, pulsed, 1  $\mu$ s to DC  
LaB<sub>6</sub> cathode, 100  $\mu$ m spot size

15 cm long 'circular' plates  
~2.5 cm diameter

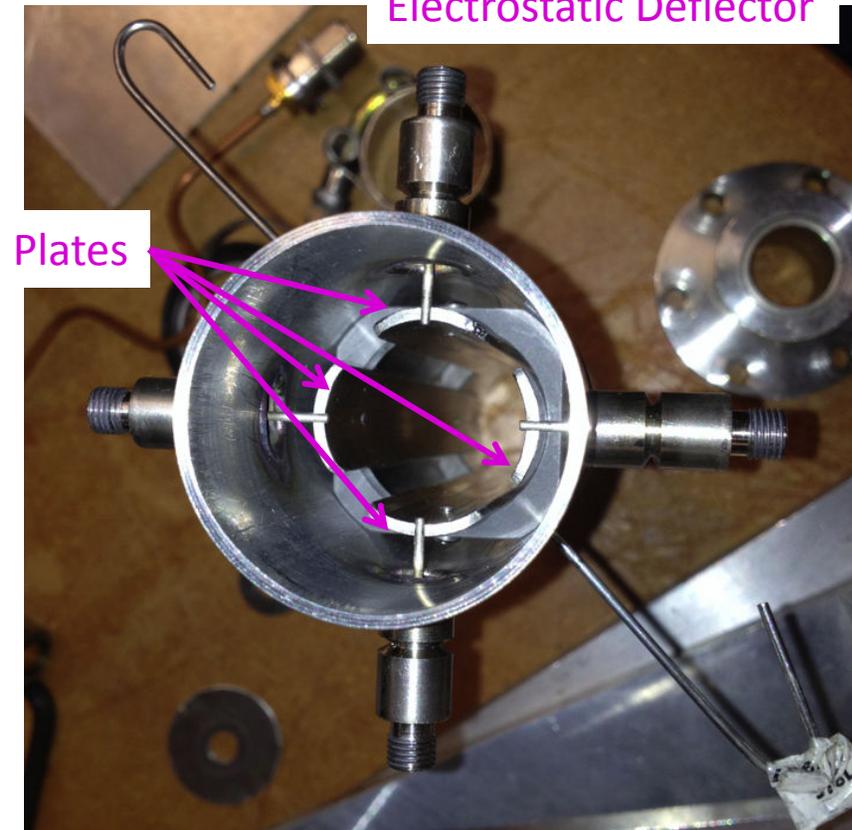
## Thermionic Electron Gun



Solenoid and  
steering magnets

Cathode

## Electrostatic Deflector





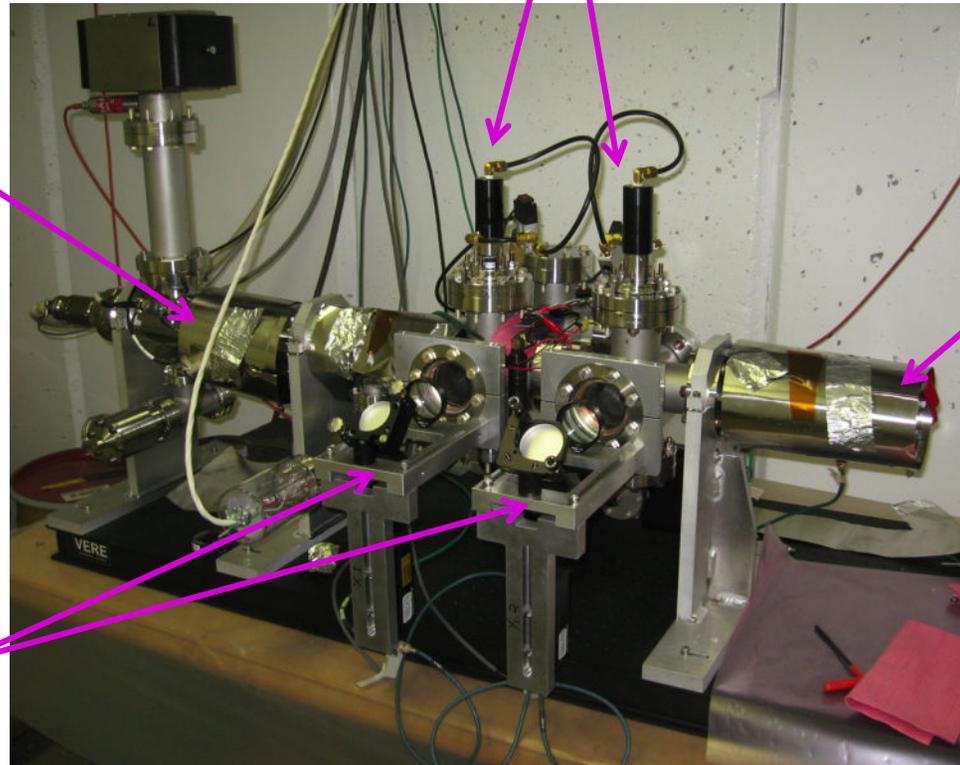
# Test Stand at NWA

Optical Transition Radiation Screens

Electron Gun

Faraday Cup

Lens / Digital  
Camera Imaging  
Systems

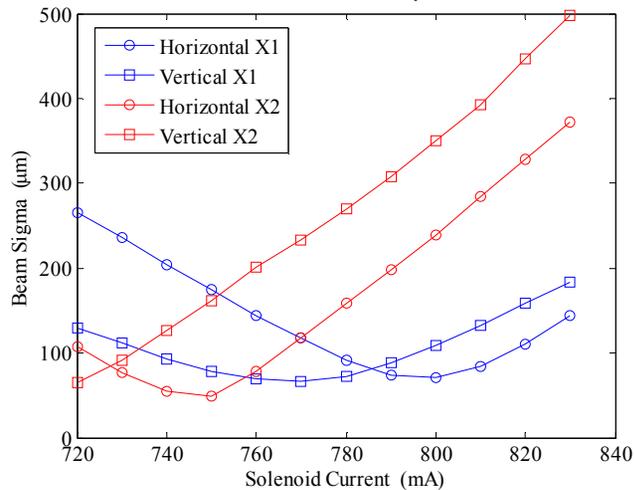




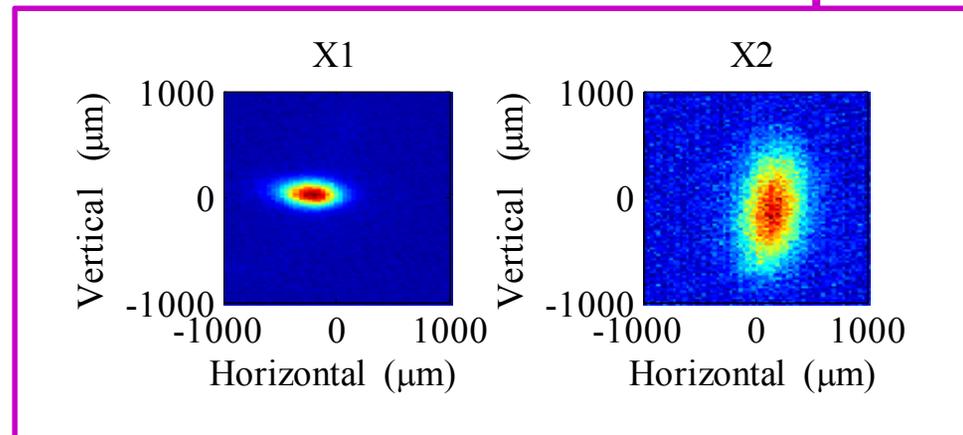
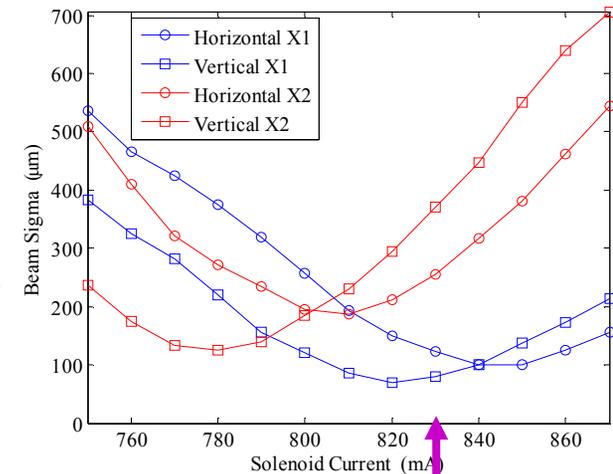
# Gun Tests

- Gun has internal solenoid
  - Scanned beam through waist at first screen

Scanned beam sizes from Ce:YAG screens (1  $\mu$ A beam)



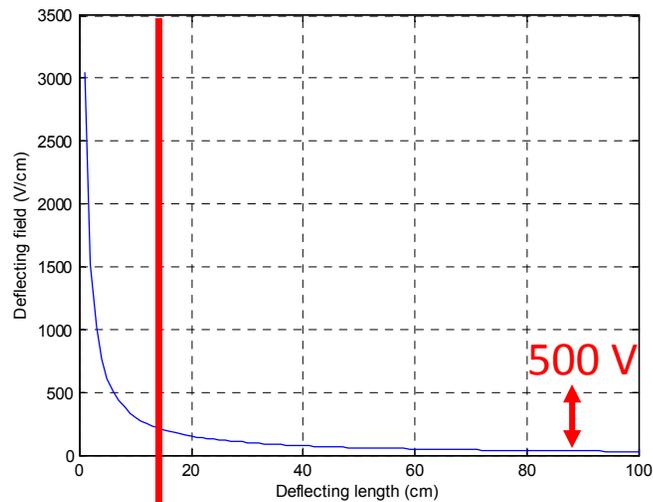
Scanned beam sizes from OTR screens (1 mA beam)



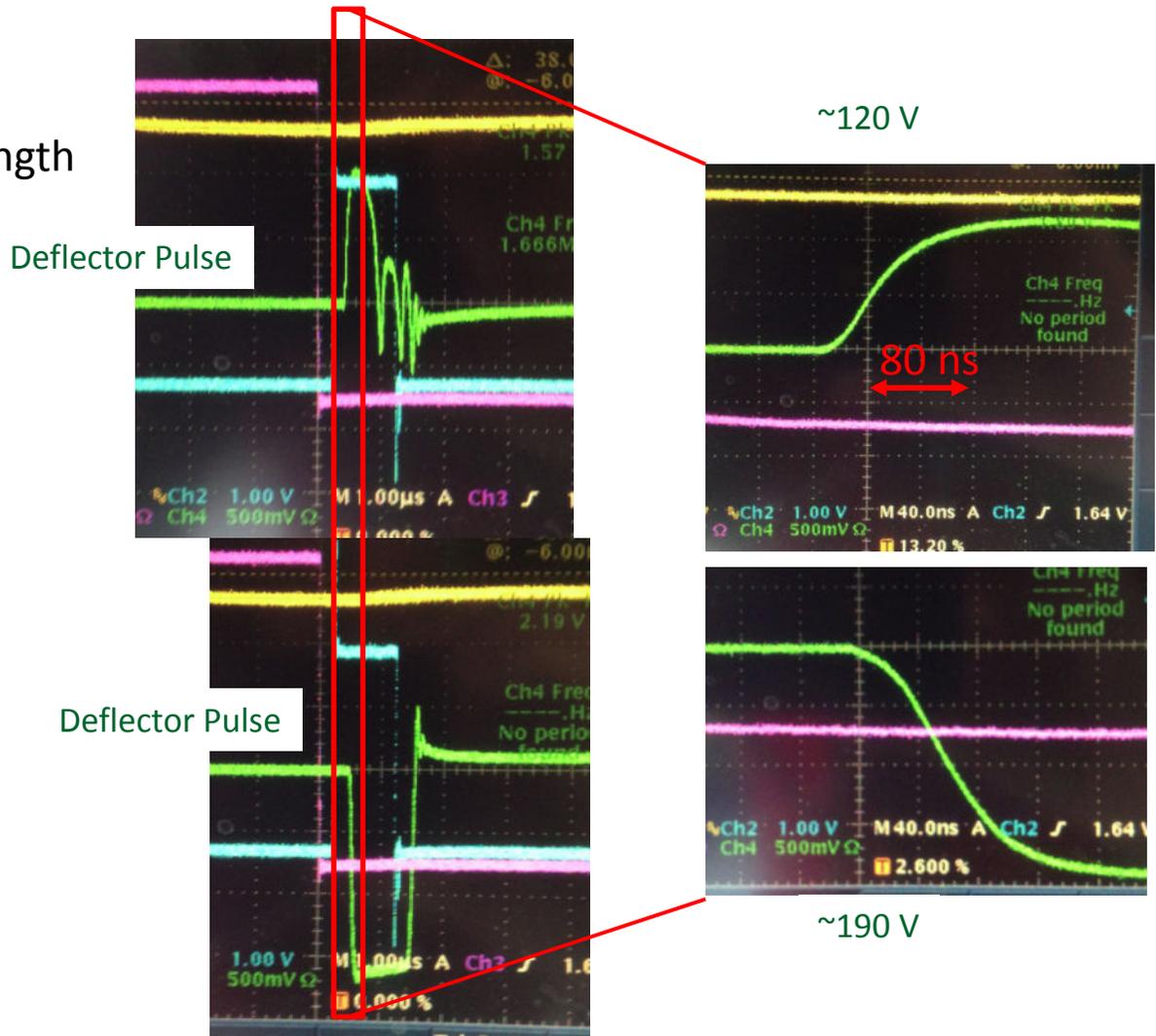


# Test of Electrostatic Deflector

Deflecting Voltage vs. Deflector Length



15 cm long plates





# Electrostatic Deflector Test

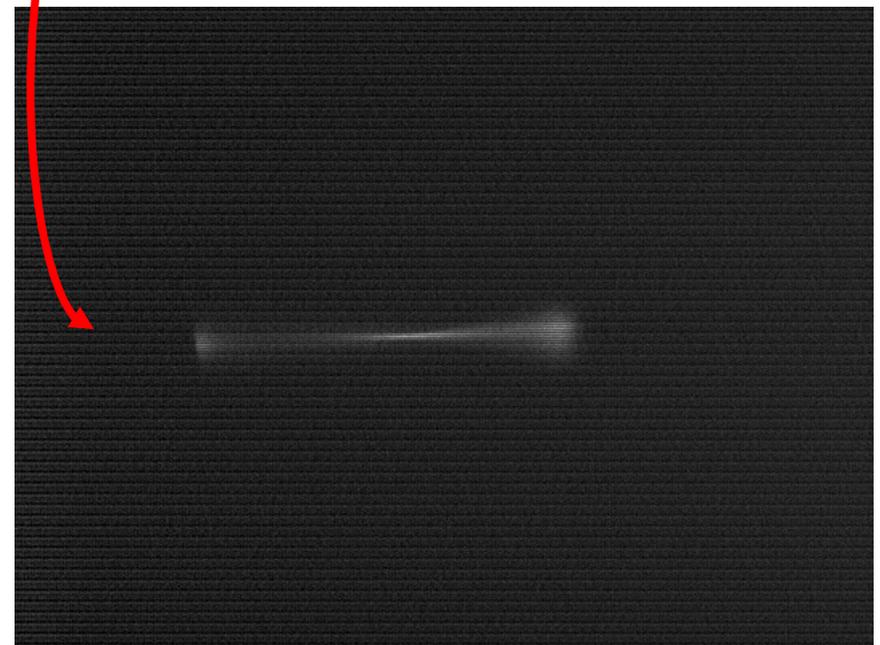
## Short sweep

- Effect is similar proton bunch passing by



## Longer sweep

- Bright part off screen
- Beam size not uniform
  - Possibly due to poor pulse quality

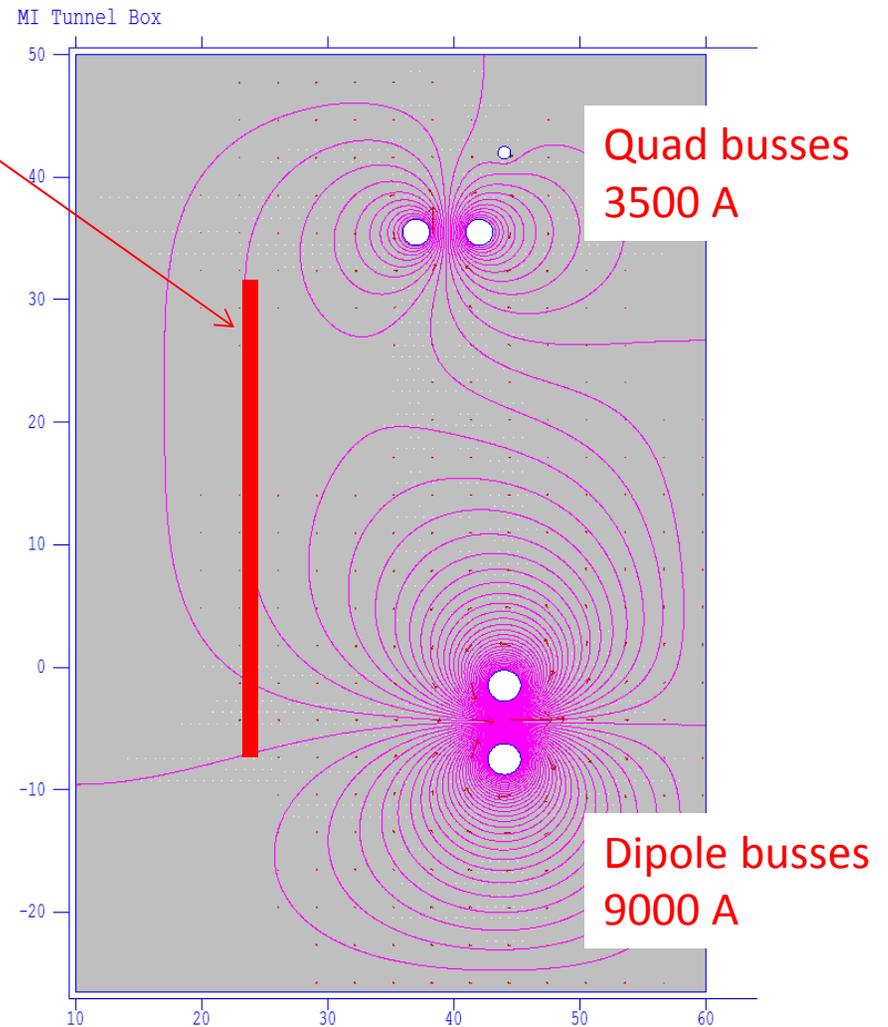
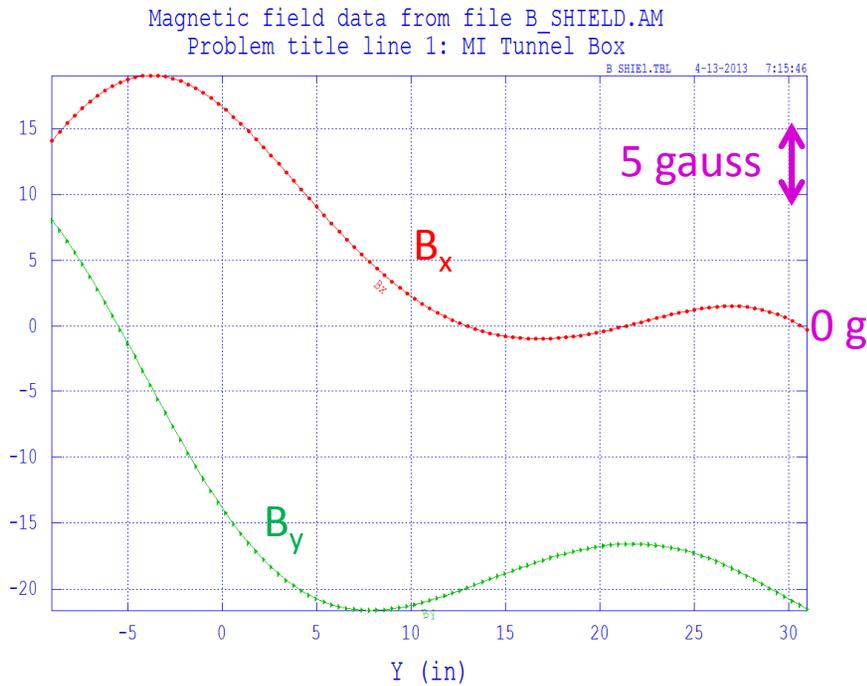




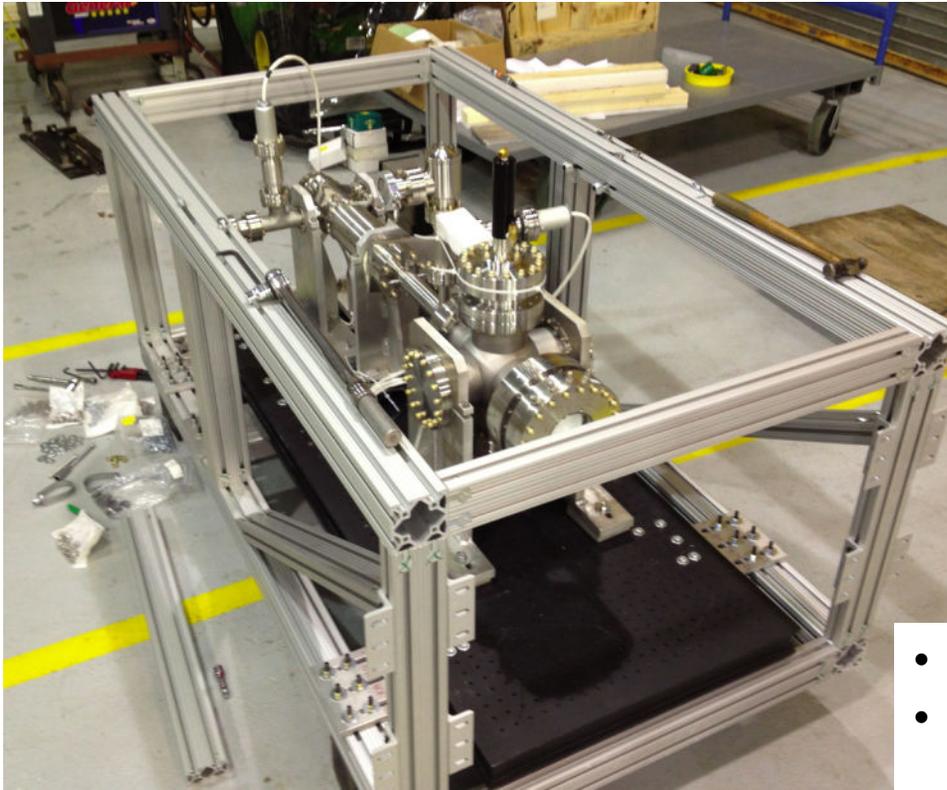
# Magnetic Fields in Tunnel

Need to shield beamline  
 First attempt will be mu metal

Electron beam



# Electron Beam Profiler

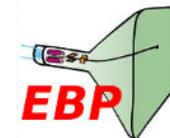


- Would like to install as soon as possible
- But...
  - Priority is “Very Low” (to put it politely)
  - Relies on the “kindness of strangers”

# Strangers (and not so strangers)

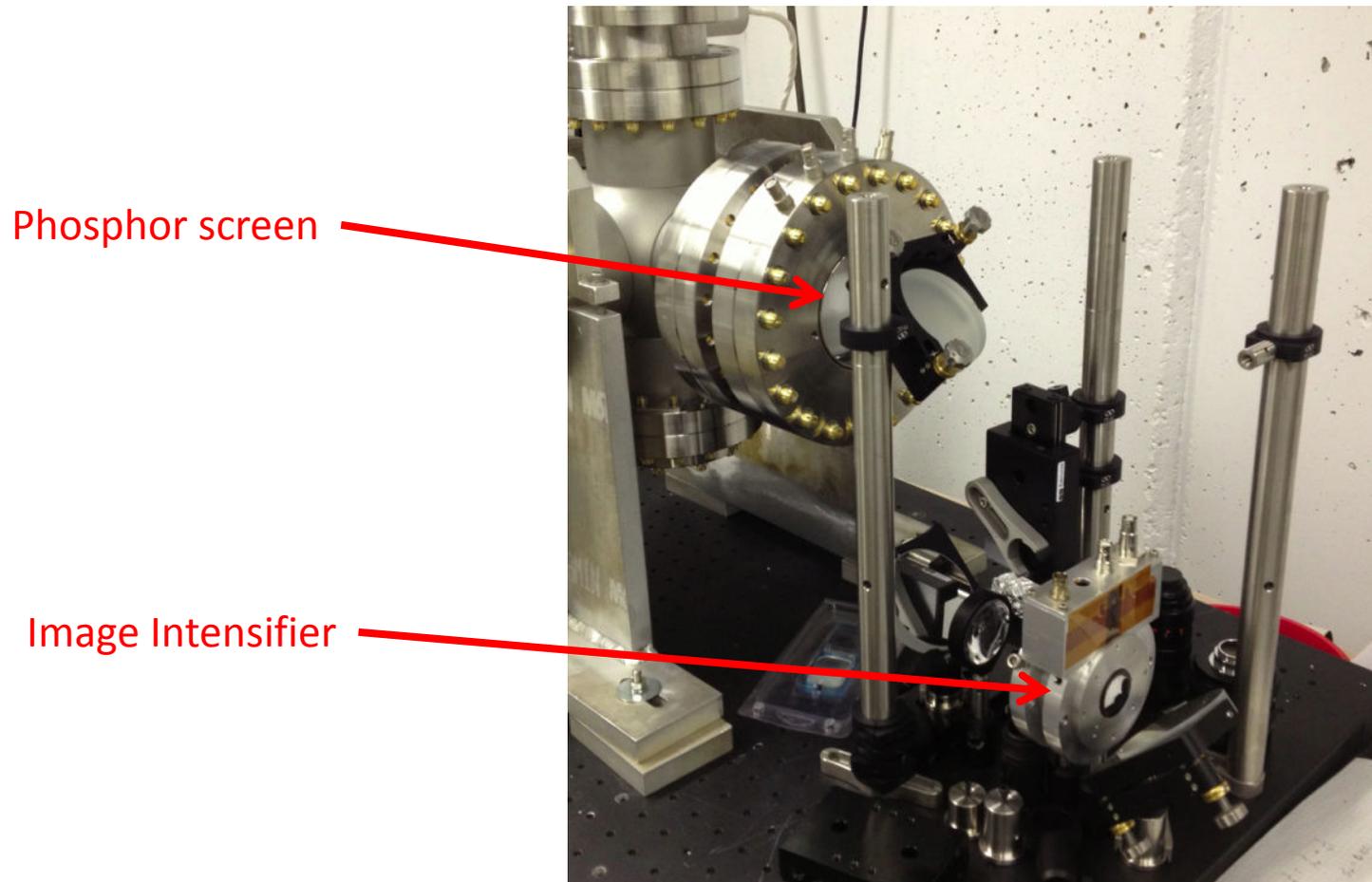
- Instrumentation
  - Amber Johnson, Carl Lundberg, Jim Galloway, Jim Fitzgerald, Peter Prieto, Pierpaolo Stabile, Andrea Saewart, Dave Slimmer, Dehong Zhang, Brian Fellenz, Alex Lumpkin
- Mechanical Support
  - Wade Muranyi, Brad Tennis, Elias Lopez, Debbie Bonifas, Scott McCormick, Ryan Montiel, Sali Sylejmani, Tom Lassiter, James Williams, John Sobolewski, Matt Alvarez, Kevin Duel
- Summer Students
  - Paul Butkovich, Khalida Hendricks, Danila Nikiforov
- Others
  - Charles Thangaraj, Dave Burk, Dennis Schmitt





# Extras

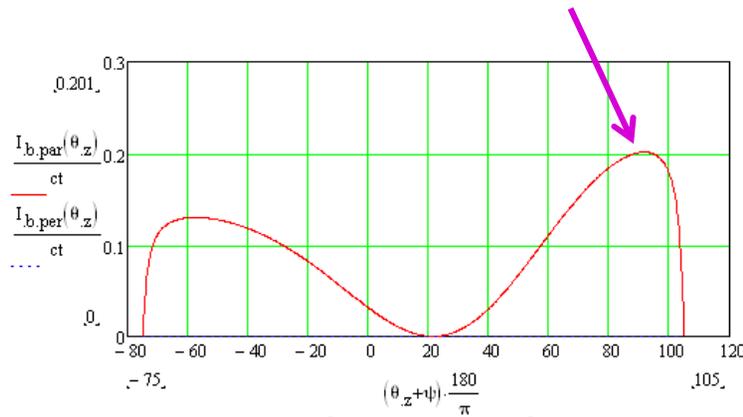
# Optics





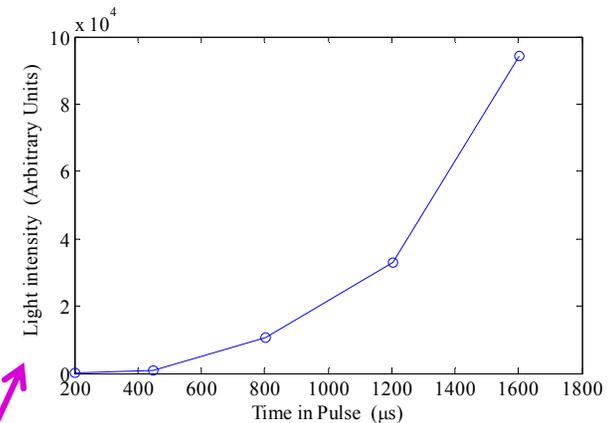
# Optical Transition Radiation

- Electron energy low
  - Broad angular distribution
  - Mirror should be  $15^\circ$  instead of  $45^\circ$

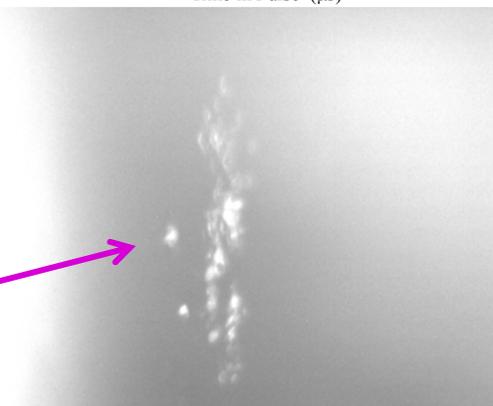


(E. Bravin, private communication)

Light yield over the 2 ms electron pulse



- Initial beam images determined to be blackbody
  - No polarization
  - Intensity increased nonlinearly with duration
  - Damage to stainless steel mirror observed





# Wire Tests

- Wire to simulate proton beam
- e Beam pulsed on for 40  $\mu\text{s}$
- Wire pulsed for 20  $\mu\text{s}$
- Half the time the beam is deflected

